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DIGITAL DATABASE DEVELOPMENT AND SEISMIC CHARACTERIZATION AND CALIBRATION FOR THE MIDDLE EAST AND NORTH AFRICA

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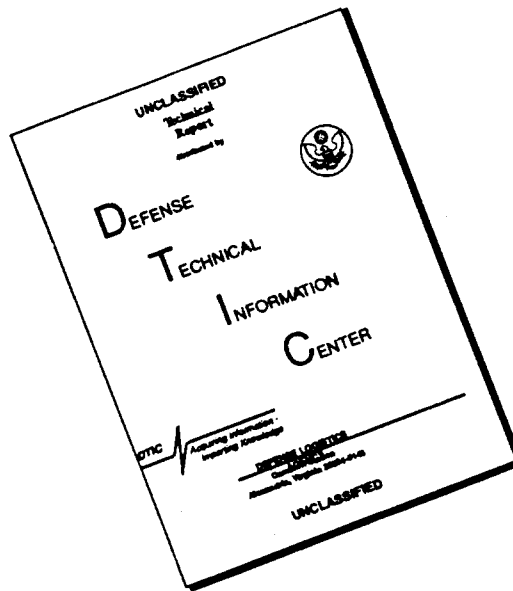31 July 1996

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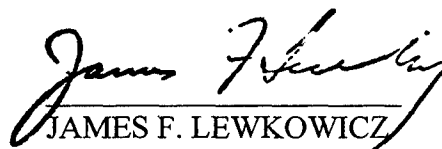Office of Non-Proliferation and National Security

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It is essential for the CTBT monitoring efforts that multidisciplinary information on any given region is readily available and accessible in a digital, on-line format via electronic networks for use by concerned researchers and decision makers. Our objective is to collect and organize all available seismological, geophysical, and geological data sets for the Middle East and North Africa into a comprehensive Geographic Information System (GIS). In addition, we are producing original results, such as crustal structure beneath available broadband seismic stations, in areas where there is no available information. We are distributing the organized databases in ArcInfo GIS format and menu driven access tools and with a specially designed World Wide Web (WWW) server. Among the already collected digital data sets are detailed Moho and basement maps for the Middle East region, seismicity catalogs, focal mechanisms, and tectonic fault maps, mine locations, and various types of geophysics/geologic/geographic data for the region. We have also developed metadata to document the resolution and accuracy of the already organized data sets. The developed organized system and its efficiency in using and updating it will help CTBT researchers and decision makers to reach a conclusion in a very short time, including analyses of special (suspect) events and On Site Inspection efforts. Our World Wide Web address for data distribution is http://atlas.geo.cornell.edu.

14. SUBJECT TERMS

			15. NUMBER OF PAGES 80
Middle East	Moho	Geographic Information System	
North Africa	2-D models	Geology	**16. PRICE CODE**
Crustal Structure	Seismology	Satellite imagery	
	Geophysics	WWW	

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1. INTRODUCTION

With the anticipated completion of a multilateral comprehensive nuclear test ban treaty in the near future, it is essential for monitoring efforts that multidisciplinary "reference" information on any given region is readily available and accessible in a digital, on-line format via electronic networks or on host computers for use by concerned researchers and decision makers. We are building, organizing, and updating a digital geophysical and geological information system for the Middle East and North Africa region and conducting original seismological studies to characterize and calibrate complex tectonic structures of the region for the purpose of adding accurate results into the developed GIS databases. Our databases and results will be of direct relevance to the US efforts in enhancing regional seismic monitoring and discrimination capabilities, and to the implementation and operation of the US NDC and monitoring efforts.

Crustal and lithospheric structure variations as well as major topographic relief along regional seismic wave propagation paths and at the source and receiver sites are crucial information to understand the excitation and propagation of high-frequency regional seismic phases, and other aspects of the problems of verification and estimation of the yield of nuclear and chemical explosions. We digitized all available crustal scale profiles in the Middle East region. By using these interpretations we produced a more detailed and accurate Moho and basement maps which can be used in modeling efforts. We developed the first digital tectonic map of the Middle East. We are also concentrating on "metadata" information for all the developed databases. Each data set entered into the system is accompanied by type of information indicating resolution, accuracy, limitations of the databases. Data access tools are also an important part of the whole system, since it would be very cumbersome to access a specific data set among all types of databases that are kept on the system. The newly developed system allows a user to search, manipulate, and interact with the databases with ease and efficiency.

1

2. DIGITAL DATABASE DEVELOPMENT FOR THE MIDDLE EAST AND NORTH AFRICA

We continuously add more information into our database in order to construct a complete crustal structure database as well as other types of geophysical and geological databases for the Middle East and North Africa. The database system is divided into four different categories: Geographic, geologic, geophysical, and imagery. In this annual report, we present all available data and access tools that we have developed during the past year. The entire database system is developed on an ArcInfo GIS system. All data are kept in ArcInfo format and can be accessed through custom designed, menu-driven access tools. The entire system is self sufficient and requires no prior knowledge of ArcInfo software commands. A user can search, study, manipulate, download and make hard copies of any parts of the database using this menu-driven system. One of the biggest advantage of the developed system is that all the data are available in one computer and the user can select and display any parts of the various databases. Multiple layers of data sets can be displayed in the same graphic window allowing the user to comprehend the study area in its entirety.

2.1. Menu Driven Access to Cornell Databases

Accessing the entire database is through the main control menu (Figure 1). A colored topography image showing the Middle East and North Africa region is also displayed on a separate window (Figure 1). This is the default setting. The main menu includes several buttons grouped together according to their functionality, such as map parameters buttons, database access buttons, map display buttons, and various system and auxiliary buttons. There are two types of buttons used in the menu driven systems: check buttons, and regular buttons. Check buttons are usually used in displaying any individual data sets and are activated as soon as they are checked. The regular menu buttons are used for either an action or to start up a new sub menu. The ones starting up additional sub-menus are indicated by three dots at the end of the function names.

Figure 1

2.1.1 Map Parameters

This section in the menu system is used for setting up a map area to work on and to annotate the map. There are four regular menu buttons each starting a new sub menu.

Set map limits

Set map limits button is used for establishing a region of interest in the Middle East and North Africa region. The region of interest is set either by clicking on one of the three regional area buttons: Middle East and North Africa (this is the default), Middle East, and North Africa or by just typing the latitude and longitude values of the lower left and upper right longitude and latitude values of the area of interest, respectively (Figure 2). *Done* and *Cancel* buttons will quit this sub-menu with or without performing the action, respectively.

Set map projection

Set map projection button allows one to select a map projection to be used during the session (Figure 2). It is possible to change the projection at any time during a session. All data sets except imagery and gridded data sets are stored in geographic coordinates. Map projection is handled on the fly as one requests a new data set to be plotted in the graphics window. The default projection is Mercator. All image and grid files are stored in Mercator projection. In order to display them Mercator projection must be defined. A warning message will be displayed if a user attempts to display an image file when a different projection is active. In this release there is no option of using a user defined projection. This will be added to the system in future releases.

Latitude longitude grid

This button is used to add a latitude longitude grid and grid labels to the map. A sub-menu allowing a user to choose grid interval, and label interval and their locations appears on the screen (Figure 3). After typing desired numbers and

Figure 2

ARCPLOT

Pan/Zoom ▾ x,y: 17.30000,0.95000   dist: 1
            dx,dy: 10.79163,-2.11348

CORNELL DATABASE 1.1

CORNELL GEOLOGY

HELP

MAP PARAMETERS ...

Set maplimits...
Set map projection...
Latitude Longitude Grid ....
Add Legend ...

DATASETS ...

Geographic Data Sets ...
Geophysical Data Sets ...
Geological Data Sets ...
Images/Grids ...

USER INPUT ...

Run ArcPlot commands ...

DISPLAY PARAMETERS ...
Zoom in   Zoom out
        Redraw
Line/Marker/Shade Sets ...
Hardcopy...

MENU-SYSTEM FUNCTIONS ...

Save algorithm ...
Load algorithm ...
Clear & Reset All Variables
        QUIT MENU

Create   a reference

HELP

On Off

GRID SPACING (in dd)

Longitude 10   latitude   10

Label every   10   (deg) longitude
Label every   10   (deg) latitude

Longitude labels at   TOP BOTTOM

Latitude labels at   LEFT RIGHT

Grid label format   DD DDM DMS

                CANCEL   DONE

Geographic   Data

HELP

GEOGRAPHIC DATASETS ...

☑ Shade land
☑ Shade oceans   HELP
☑ Coast lines   metadata...
☑ Country borders
☑ Rivers
☐ Lakes
☐ Main roads
☐ Main cities

Select and shade some countries...

                CANCEL   DONE

40°
60°   30°
         50°   20°
                  40°
30°   10°

Figure 3

checking the *On* button, the grid is displayed once the *Done* button is clicked. It is also possible to set the label format with this menu. Grid label formats are *DD, DDM,* and *DMS* representing Decimal Degree, Decimal Degrees - Minutes, and Decimal Degrees - Minutes - Seconds , respectively.

Add legend

This button is used to add a legend for the map that is displayed on the screen. Not all data sets can be seen in the legend. It is possible to have items like tectonic units, mine location, crustal profile locations, but items like coast lines, country borders will not appear in the legend box. It is automatically determined which items are displayed on the screen and appropriate items are placed in the legend box position and scale of which can be adjusted manually to fit the screen.

2.1.2 Data Sets

Under the data sets segment of the main menu there are four buttons representing our four categories of data classes: Geographic, geophysical, geological, and images/grids. This segment forms a bridge to access the entire Cornell databases on the Middle East and North Africa region.

Geographic data sets

Geographic data sets are kept and accessed through this menu button. All geographic data sets were extracted from the Digital Chart of the World CD-Rom. The data are from 1,000,000 scale maps. We extracted polygons covering land and ocean areas in the Middle East and North Africa region as well as coast lines, country borders, rivers, lakes, main roads, and main city locations. All of these data are accessible through check buttons which get activated as soon as they are checked. Figure 3 shows an example of how this menu is used. The metadata related to these geographic data are kept under the metadata sub-menu. By clicking this menu button a new sub-menu is activated and the user is asked for which data set metadata information is needed (Figure 4). In a text window detailed explanations are displayed.

Geographic   Data

GEOGRAPHIC DATASETS ...

- ☑ Shade land
- ☑ Shade oceans   HELP
- ☑ Coast lines
- ☑ Country borders   metadata...
- ☑ Rivers
- ☐ Lakes
- ☐ Main roads
- ☐ Main cities

Select and shade some countries...

CANCEL   DONE

metadata

METADATA FOR ...

- ☐ Shade land and oceans
- ☐ Coast lines and country borders
- ☐ Rivers
- ☐ Main roads
- ☐ Main cities

About all of them...

CANCEL   DONE

Text

DATA LINEAGE INFORMATION FOR ALL THE "DATA CHART OF
THE WORLD" DATABASE

Source: Digital Chart of the World for use with
ARC/INFO software. Environmental Systems Research
Institute, 1993.

Modifications to the database

Any coverage was originally composed by many tiles that
represented 5 degrees by 5 degrees on the globe. Tiles with
identical attributes have been appended to be used in this
application. The following is metadata obtained from the
"Data Chart of the World" (DCW) CDROM.

This table documents the lineage characteristics of the 1:1,000,000-
scale component of the Digital Chart of the World (DCW) database. It
supplements information in the DCW Data Quality Table (DQT), a standard
VPF table residing at the DCW library level that is the main repository
of information on source data characteristics. This table contains
information on development techniques that are common to all DCW
1:1,000,000-scale library coverages. Information specific to individual
feature classes (including special processing techniques, feature
coincidence between classes, and database design issues) can be found in
narrative files associated with master feature tables at the coverage
level of the database. These narrative files are present within
individual coverage directories and use a naming convention of the
feature class name followed by a .DOC suffix. Quality attributes that
vary spatially are stored in the DCW Data Quality (DQ) coverage.

General Production Process:

All DCW coverages are derived from copies of color/feature film
separates on 7-mil stable Mylar or acetate prepared from original
Defense Mapping Agency (DMA) negatives that are used in the Operational
Navigation Chart (ONC) lithographic production process. The number of
separates available for each source chart varied from 7 to 30 pieces.
Following reproduction, separates underwent an extensive map preparation
process to verify registration tic coincidence between separates and to
inventory the data present on each sheet. Where necessary, data
represented with broken line symbols on the source were manually
connected into continuous lines to facilitate the automation process.
For example, the dash/dot symbols used to represent intermittent
drainage were connected with drafting ink to become continuous, smooth
flowing lines. Map preparation tasks were verified through independent
quality control inspection.

Following map preparation, the data were automated. Point features were
manually digitized using large format CalComp 9100 digitizing boards.
All line features were captured through optical scanning on a SCAN-
GRAPHICS CF1000 scanner at a resolution of 500 dots per inch (dpi).
Nearly all data were vectorized using SCAN-GRAPHICS RAVE software
resident on a DEC VAX 6320 minicomputer. Some utility line data were
captured using Hitachi CadCore Tracer software in conjunction with 300-
dpi scanned images. Vector output files were converted to a DXF format
and transferred to the main processing environment.

Following scanning/vectorization, the data were converted into an
ARC/INFO coverage format (ver 5.0.1) in a SUN SPARC processing

CONTINUE PAUSE   Quit

Figure 4

It is also possible to highlight the boundaries of a country by using the "select and shade some countries" button. This button activates another sub-menu which allows one to select a few country names to be highlighted. This can be used when a user is working on a country and wants to highlight it to differentiate from the surrounding countries.

Geophysical data sets

Geophysical data sets are grouped under three different categories: Seismicity related, seismic station coverage, and crustal scale cross sections (Figure 5). We have entered the two main earthquake catalogues available for the past several years, the USGS PDE catalog, and the International Seismological Center's earthquake catalogue. The PDE catalog covers all events between 1960 and 1990 in the Middle East and North Africa region. The ISC catalogue covers seismicity between 1987 and 1992. All attributes related to each event such as location, depth, origin time, magnitude are also entered into the system. In Figure 5, an example of the ISC seismicity catalogue is shown for a selected region in the Middle East. The symbols are automatically scaled to events' magnitudes, and it is possible to obtain information on any event by clicking on the event with the mouse.

The third kind of data set developed is the Harvard earthquake focal mechanism solutions. A sub-menu allows the user either to choose all focal mechanisms to display or select a region or select a specific event and display the focal mechanisms. It is also possible to see all attributes of any selected event in the database (Figures 6 and 7).

Another type of geophysical data set is the locations of short period and broad band seismic station locations in the Middle East and North Africa region (Figure 8). Although the list is not complete at this time in the near future we will be adding more local network stations from the other countries of the region. The broad band station coverage, however, is complete. Each broad band station also includes basic information about them such as which seismic network that they belong to and when the station started operating. This information can be obtained by clicking the "i" button on the left and then clicking on the station of interest.

CORNELL DATABASE 1.1

CORNELL GEOLOGY

HELP

MAP PARAMETERS ...

Set maplimits...
Set map projection...
Latitude Longitude Grid ....
Add legend ...

DATASETS ...

Geographic Data Sets ...
Geophysical Data Sets ...
Geological Data Sets ...
Images/Grids ...

USER INPUT ...

Run ArcPlot commands ...

DISPLAY PARAMETERS ...
Zoom in   Zoom out
          Redraw
Line/Marker/Shade Sets ...
Hardcopy...

MENU-SYSTEM FUNCTIONS ...

Save algorithm ...
Load algorithm ...
Clear & Reset All Variables
QUIT MENU

Geophysical   data

HELP

- SEISMICITY
metadata

⬤   Plot all seismicity

⬤ ⊔ PDE Catalog
        Plot selected events...

⬤ ☑ ISC Catalog

⬤ ⊔ CMT Catalog
        Plot focal mechanisms ...

- SEISMIC STATION LOCATIONS
metadata

⬤ ⊔ Short period stations

   ⊔ Broad band stations

- CRUSTAL SCALE CROSS SECTIONS
metadata

⬤ ⊔ Display profile locations

      display crustal x-sections...

CANCEL   DONE

ARCPLOT

Pan/Zoom ⬡ x,y: 21.15000,7.60000   dist: 15.32832
         dx,dy: 14.64163,4.53652

Figure 5

Figure 6

Geophysical data

HELP

– SEISMICITY
metadata

Plot all seismicity

ⓘ ⊥ PDE Catalog
Plot selected events...

ⓘ ⊥ ISC Catalog

ⓘ ☑ CMT Catalog
Plot focal mechanisms ...

– SEISMIC STATION LOCATIONS
metadata ⓘ ⊥ Short period stations
⊥ Broad band stations

– CRUSTAL SCALE CROSS SECTIONS
metadata ⓘ ⊥ Display profile locations
display crustal x–sections...

CANCEL   DONE

focal_mechanisms

Options:
----
select area
select one event
clear selection

x–offset (deg):   7
y–offset (deg):   –5

compressional color ...
dilatational color ...
offset line color ...

Scaling factor   1.   ☑ Scale by magnitude
Symbol size =   1.   ⊥ Fixed symbol size

Cancel   Done

ARCPLOT

Pan/Zoom ▽   x,y: 22.85266,0.47022   Area: 84.30785
dx,dy: 19.51411,–15.32915   dist: 24.81498

	1135	
AREA	=	0.000
PERIMETER	=	0.000
CMT#	=	1135
CMT–ID	=	1135
DIP_RAKE	=	–40_0
SYMBOL	=	269
DATE	=	04/23/79
HOUR	=	13
MIN	=	1
SEC	=	58.6
SECCOR	=	–3.0
LAT	=	31.240
LON	=	35.460
CODE	=	MLI
DEPTH	=	33.0
STRIKE	=	197
DIP	=	40
RAKE	=	–4
STRIKE2	=	291
DIP2	=	87
RAKE2	=	–130
EIGVAL1	=	5.89
PLUNGE1	=	30
STRIKEA	=	53
EIGVAL2	=	–0.01
PLUNGE2	=	40
STRIKEB	=	293
EIGVAL3	=	–5.88
PLUNGE3	=	35
STRIKEC	=	167
T_MOMENT	=	5.89
EXPONENT	=	23
MRR	=	–0.44
MRR_ERR	=	0.52
MSS	=	–2.12
MSS_ERR	=	0.73
MEE	=	2.55
MEE_ERR	=	0.34
MRS	=	4.25
MRS_ERR	=	1.16
MRE	=	–1.41
MRE_ERR	=	1.48
MSE	=	–3.01
MSE_ERR	=	0.47
MB	=	5.1
MS	=	4.3
NUM_STA	=	8
NREC	=	18
ICUT	=	45
MWSTA	=	0
MWREC	=	0
MICUT	=	0
CLAT	=	30.540
CLAT_ERR	=	0.19
CLON	=	35.590
CLON_ERR	=	0.16
CDEPTH	=	15.0
CDEPTH_ERR	=	–1.00
X–COORD	=	35.590
Y–COORD	=	30.540

CONTINUE PAUSE   Quit

40°   50°   60°
30°
20°

Figure 7

Figure 8

Crustal scale profile locations and their interpretations also form a significant part of the geophysical databases. Figures 9 and 10 show the profile locations. The interpretations of selected three profiles are shown in Figure 10. Both gravity and seismic refraction profiles were digitized and entered in the database system. Each interface is assigned values representing either seismic velocity or density values above and below the interfaces. These profiles can be dumped into an ASCII file for future use in modeling programs. These profiles are also used as constraining points to a more detailed Moho and basement maps that are being developed for the region.

We also added information about the quality of the profiles. These kinds of information can be obtained by selecting the "i" button and then clicking on any profile in the database (Figure 9).

Geological data sets

Geological data sets are the third kind of databases that are under development. Up to the present time we have developed a complete tectonic map of the Middle East region and mine locations in some selected countries (i.e., Iran, Iraq, Libya, Algeria). The tectonic map of the Middle East is composed of nine separate elements: Faults, volcanics (Neogene/Quaternary), volcanics (Paleogene), ophiolites, volcanoes active, volcanoes (inactive), basement outcrop locations, basement depth contours, and some major depression locations (Figure 11). Each of these items are digitized from several maps from individual countries and merged carefully to have this first digital tectonic map of the region. Any of these nine features was assigned appropriate attributes. For example, in order to obtain some information about a certain fault in the region, the user only needs to select the correct "i" button and then click on the fault that is of interest. Available information on the type of fault, active vs. inactive information will be displayed on the screen.

Mine locations in some of the Middle East and North Africa countries were also entered in the database. An example is shown in Figure 12. In each country shown both producing and prospect mine locations are marked separately. It is also possible to obtain information about these mine sites by simply clicking on any selected mine location. Type of mine and what is mined will be displayed on the screen in a text window.

ARCPLOT

Pan/Zoom ▽   X,Y: 29.90596,21.15888   Area: 124.55343
              dx,dy: 3.99687/18.47962   dist: 18.90692

50°   40°   30°

30°

20°

10°

☒ xsection locations

Geophysical data   HELP

– SEISMICITY
  metadata)   ● Plot all seismicity
              ⬤ ⬜ PDE Catalog
                    Plot selected events...
              ⬤ ⬜ ISC Catalog
              ⬤ ⬜ CMT Catalog
                    Plot focal mechanisms ...

– SEISMIC STATION LOCATIONS
  metadata)   ⬤ ⬜ Short period stations
                 ⬜ Broad band stations

– CRUSTAL SCALE CROSS SECTIONS
  metadata)   ⬤ ✓ Display profile locations
                    display crustal x–sections...

                    CANCEL)   DONE)

Text   ◄ ►

REFERENCES:

LENGTH   = 1165218.75000
AUTHOR   = Healy, J. H. et al.
YEAR   = B2
FIGNUMBER   = plate 9
SOURCE   = Open–file report USGS–OF–02–37
TITLE   = Saudi Arabian Seismic Deep–Refraction
              Profile: Final Project Report

Six shot points were used: five on land, with most charges placed
below the water table in drill holes, and one at sea, with charges
placed on the sea floor and detonated from a ship. Slightly more
than 61 metric tons of explosives were used in 19 discrete firings.
Seismic energy was recorded by 100 newly–developed portable seismic
stations deployed in approximately 200 km–long arrays for each
firing. Each station consisted of standard 2–Hz vertical component
geophone coupled to a self–contained analog recording intrument
equipped with a magnetic–tape cassette.

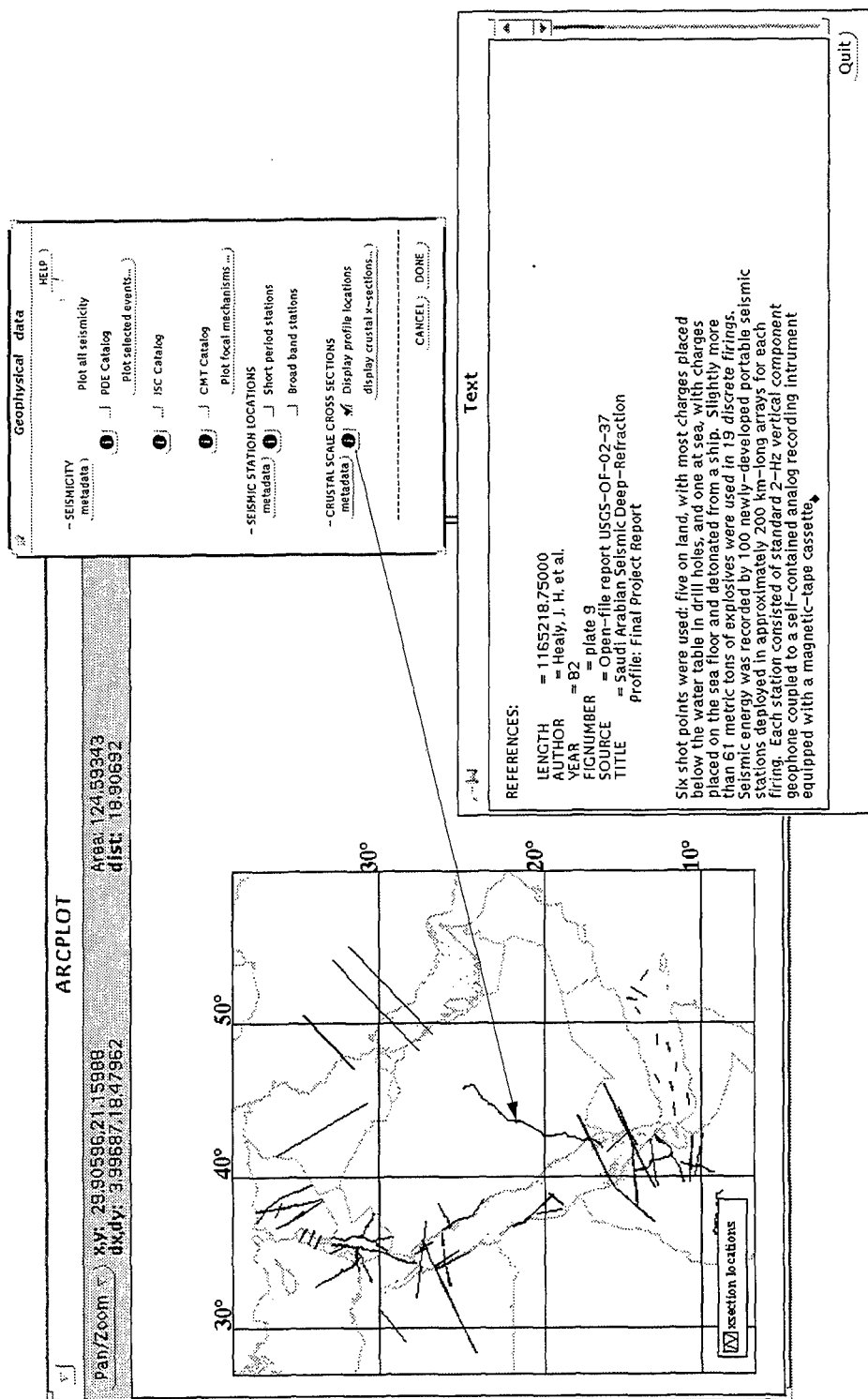   Quit)
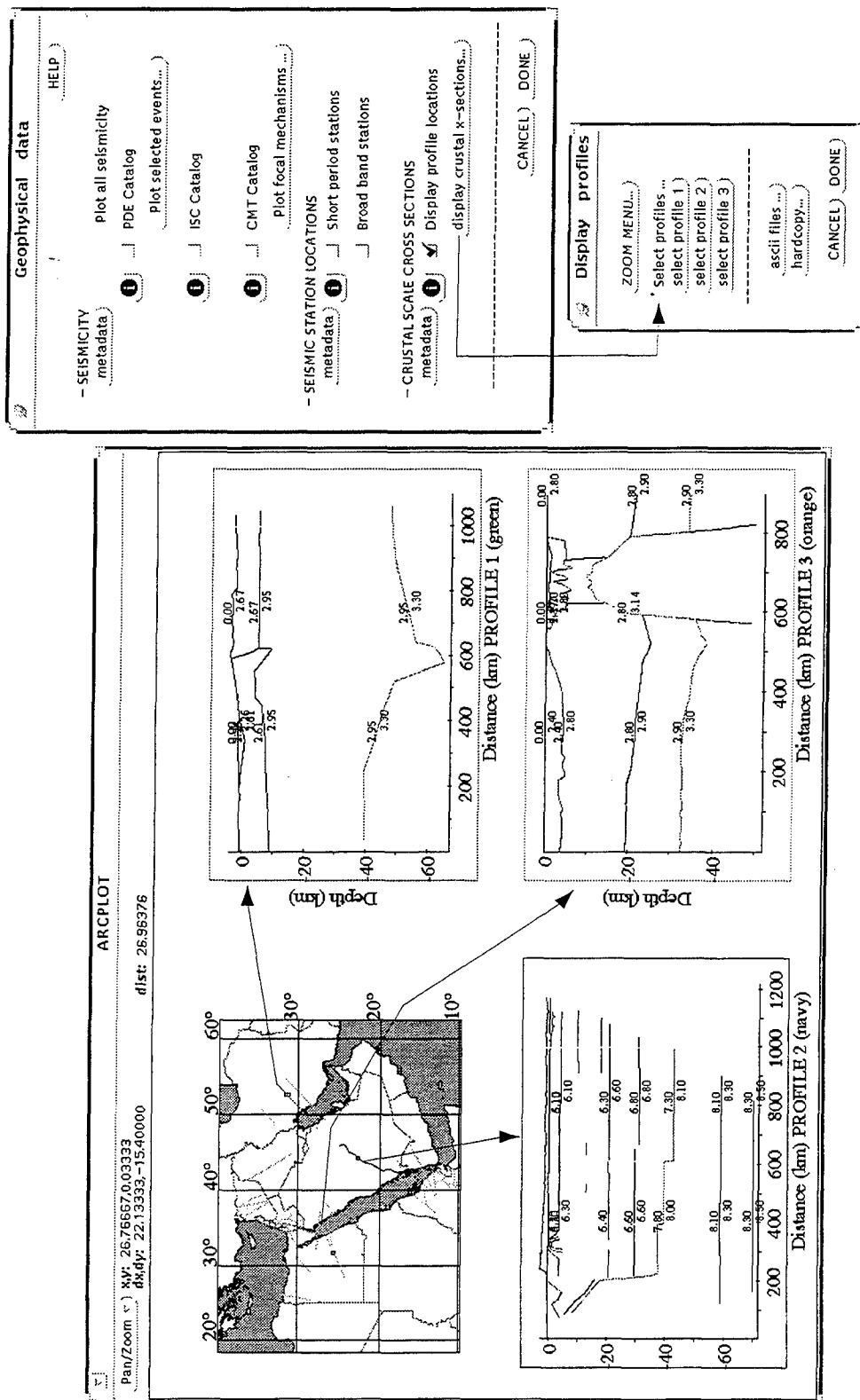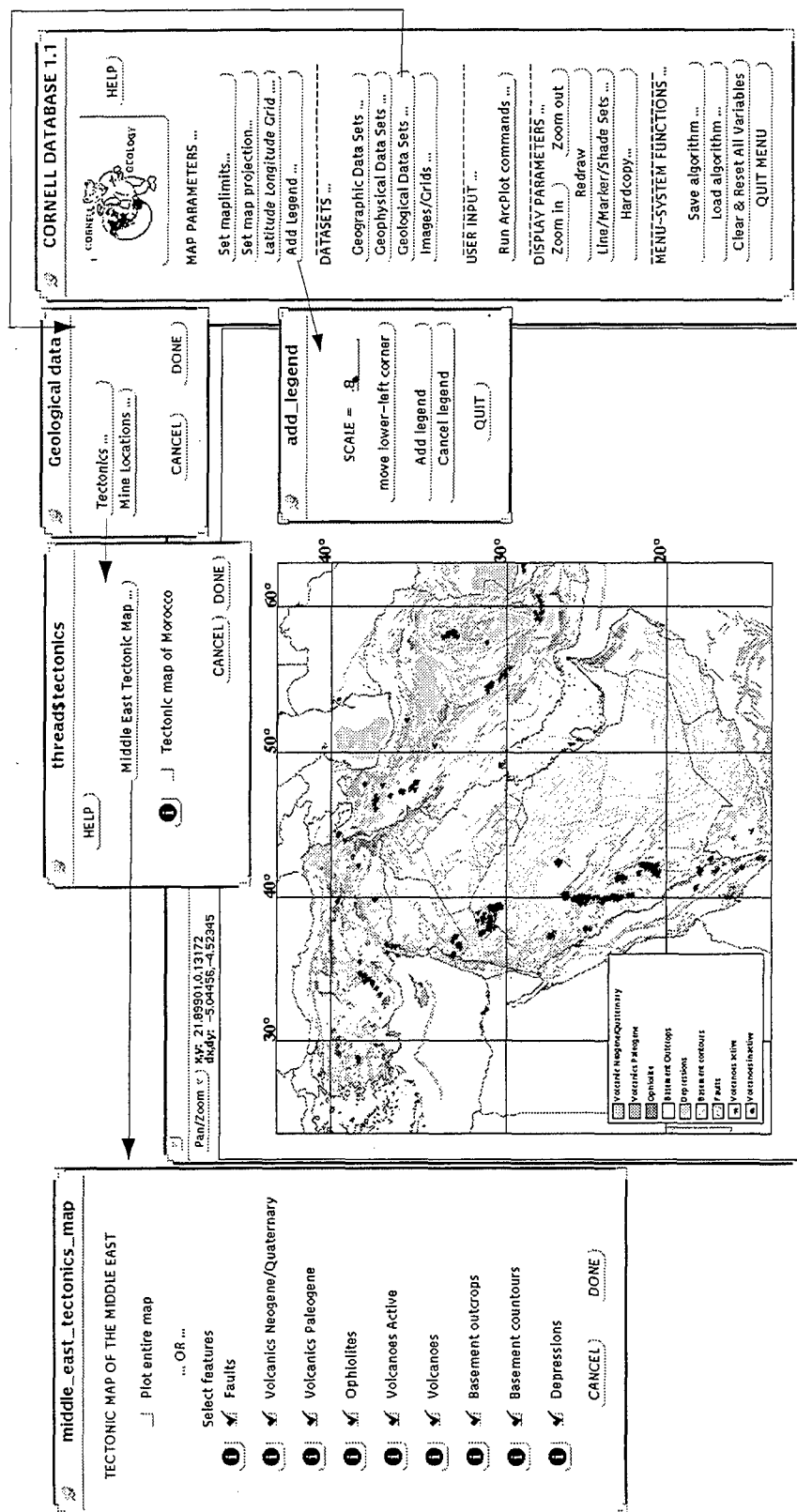
Figure 9

Figure 10

Figure 11

Figure 12

18

Images and grids

Image and grid files form the fourth type of databases. Databases included under this category include topography, hill shaded representation of topography, basement depth, moho depth, Bouguer gravity, free air gravity, and Landsat TM imagery. The topography data in our databases is 1 km in resolution and obtained from the USGS based on DMA's higher resolution topography data. We added ETOPO5's bathymetry data and merged these two data sets to obtain a full coverage for the entire area of interest (Figure 1). The second kind of topography data set is the hill-shaded representation of the same topography data. This type of representation highlights the relief and gives the image a three-dimensional perspective. The third data set under this category is the basement depth map obtained from the Institute of the Physics of the Earth (IPE) of the former Soviet Union. Although this map has accuracy problems, it still gives a first order differences in sediment thickness in the region. The fourth data set is the Moho depth map (Figure 13). This map is also obtained from the IPE publications. Similar to the basement map this map also has accuracy problems and should only be used to see the first order changes in Moho depth.

Another type of geophysical databases that are kept under the images and girdded data set is the Bouguer gravity and free air gravity values for parts of the Middle East and North Africa region (Figure 14). This map was obtained from several sources. Gravity values from Syria, Lebanon, Israel, Egypt and parts of the western Mediterranean region came from digitized contoured gravity maps. The rest of the areas have point readings. These two kinds of data sets were merged and the entire data set was gridded (Figure 14). The free air gravity values cover a smaller area and they were girdded using only point data.

Also kept under the gravity databases are original point and contour files. These can be displayed using the sub menu called "coverages used" (Figure 15). This type of data give an indication of reliability of the gridded data for a given region. The metadata button in the same menu gives further information about the data such as the source, contact person, addresses etc. (Figure 16).

Figure 13

Figure 14

Figure 15

bouguer_coverages

Coverages used to generate Bouguer grid ...

☑ North–Africa point data

☐ South–Spain & Morocco point data

☐ South–Spain countours

☐ Syria–Lebanon–Israel contours

☐ Zagros point data

☑ Egypt contours

(metadata for the coverages ...)

CANCEL) DONE)

bouguer_cov_meta

METADATA FOR THE COVERAGES ...

☐ North–Africa point data

☐ South–Spain & Morocco point data

☐ South–Spain countours

☐ Syria–Lebanon–Israel contours

☐ Zagros point data

☑ Egypt contours

CANCEL) DONE)

Text

METADATA FOR BOUGUER EGYPT CONTOURS

Source: It was digitized from a photocopy of a map whose sponsors
were: Agip, Amoco, Arco, BHP, BP, Chevron, Conoco, Exxon, Marathon,
Mobil, Philips, Placid/Hunt Int., Shell, Texaco, Total and Unocal
oil companies.

Compiled by Pierre CHEVALIER, Chris GREEN and Ian WINDLE from surveys
supplied to the University of Leeds Industrial Services (ULIS) as
part of the African Gravity Project (AGP).

Further details from
J.D. Fairhead (leeds) and A.B. Watts (Lamont)
c/o University of Leeds Industrial Services
175 Woodhouse Lane, Leeds LS2 9AR (UK)

Telephone Leeds (0532)422407
Telex 556473 UNILDS G

* University of Leeds Industrial Services 1988.

The source map is a good quality photocopy of a 1:2,000,000 scale map. The
contours represent Bouguer anomalies on land and Free Air anomalies offshore.
The original map was in Equatorial Mercator projection but after digitizing
it was stored in geographic coordinates. The coverage contains arcs with
the standard ARC/INFO attributes plus an extra attribute "GRAVITY" for the
bouguer gravity values.

CONTOURS
Gravity contours constructed from a minimum curvature derived grid of sides
5 minutes latitude and 5 minutes longitude. Isogal values in mGal.
(1 mGal = 10 g.u.).

GRAVITY DATUM
Gravity calculated using the International Gravity Formula 1967 (IGF67) and
referred to the International Gravity Standard Network, 1971 (IGSN71).

DENSITIES
Density for Bouguer correction on land 2.67 g/cc.

Bouguer gravity values computed using terrain corrections where available.
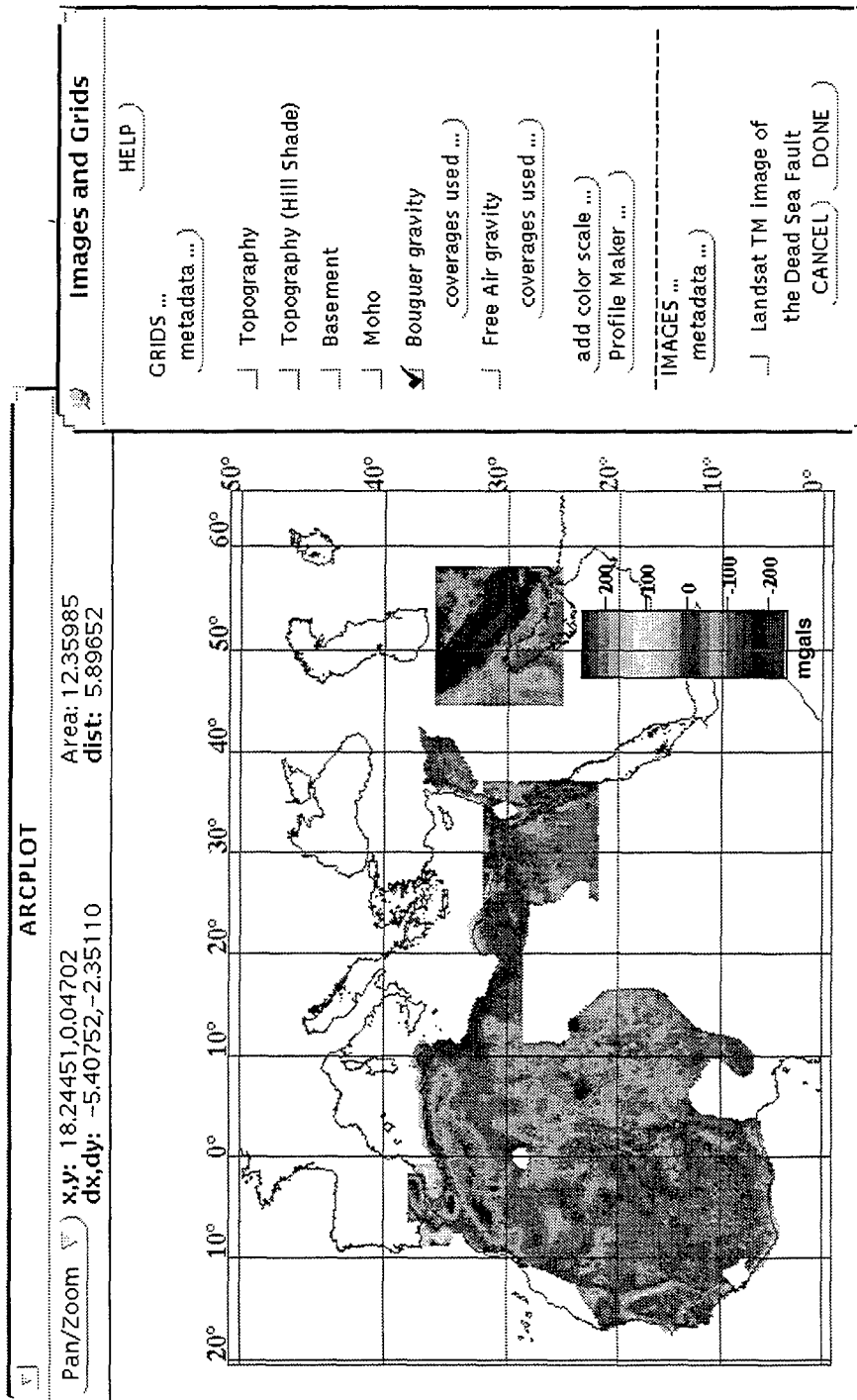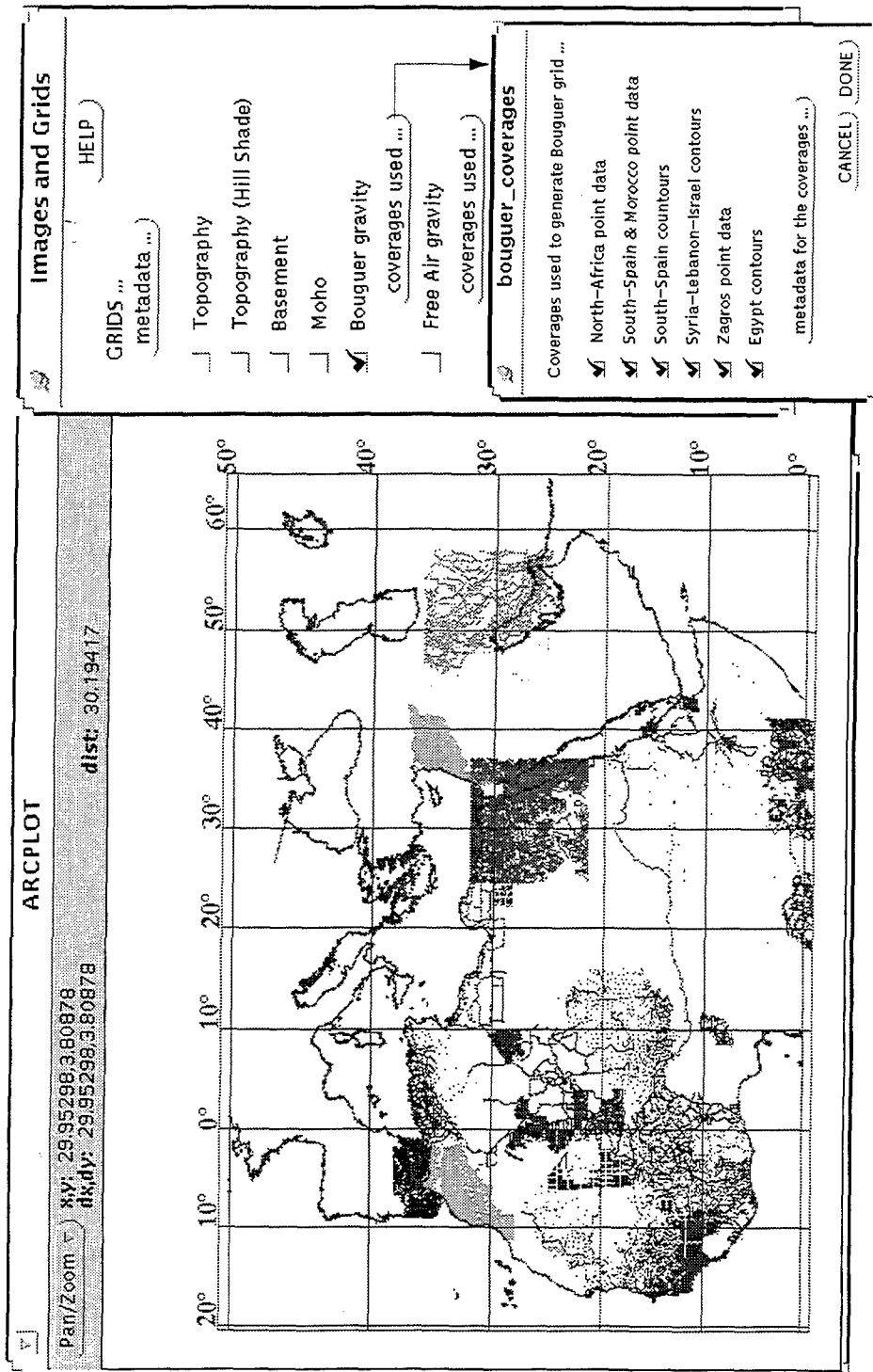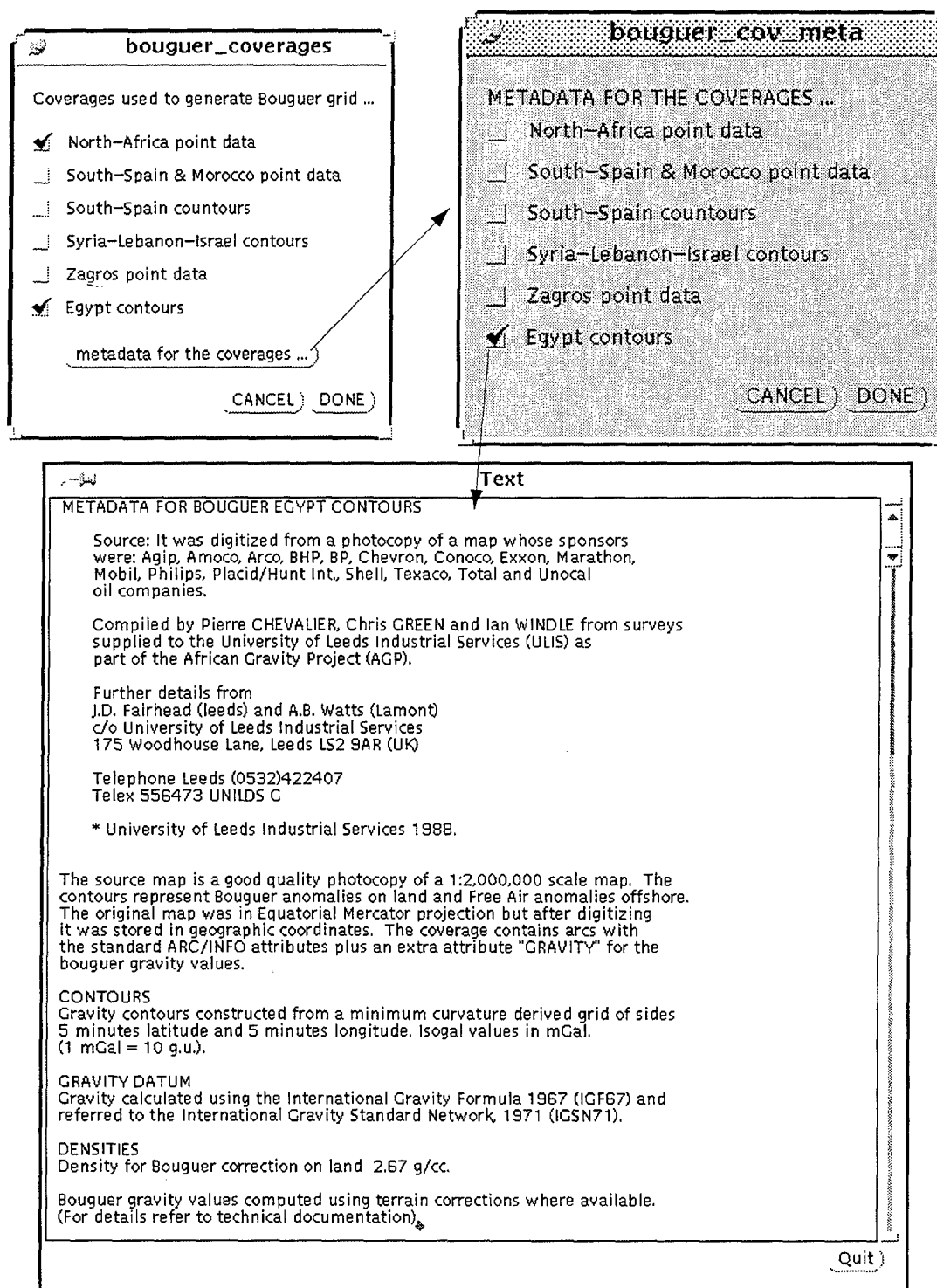(For details refer to technical documentation).

Quit)

Figure 16

23

Another important tool that was developed is the "profile maker". This tool can be used to extract profiles along two arbitrary points either typed in or selected from the screen. Using this tool one can either extract the values along two points in any of these gridded data sets or make crustal scale profiles including topography, basement, and Moho depths (Figure 17). This tool can be used to extract a profile and download the values into an ascii file that can be used with other modeling programs. For example, the crustal structure between a seismic event and station can be extracted. This 2-D crustal profilel can then be used for producing synthetic seismograms.

The last type of data under this category is Landsat TM imagery. We have a significant amount of TM coverage in North Africa and the Middle East. However, in this release we only provide a TM coverage along the entire Dead Sea fault system (Figure 18). This is a mosaic of 5 original TM scenes. The other TM scenes we have are being processed and will be made available in future releases.

2.1.3. User Input

Running ArcPlot commands

This part of the menu is designed for ArcInfo users. This menu can be used when a user wishes to add an external data set to be displayed and manipulated. The window allows five separate command lines to be executed. These lines can also include run commands to execute longer Arc Macro Language (AML) codes. Options include running the commands as first or last commands (Figure 19).

2.1.4. Display Parameters

This part of the menu system is related to map display, color changes, and hardcopy making.

Zoom in and zoom out

These two buttons are alternatives to setting map area by "set map limit" button discussed earlier. The zoom in button allows interactive zoom in on the screen instead of entering numbers. The zoom out button zooms out to whole area of the Middle East and North Africa.
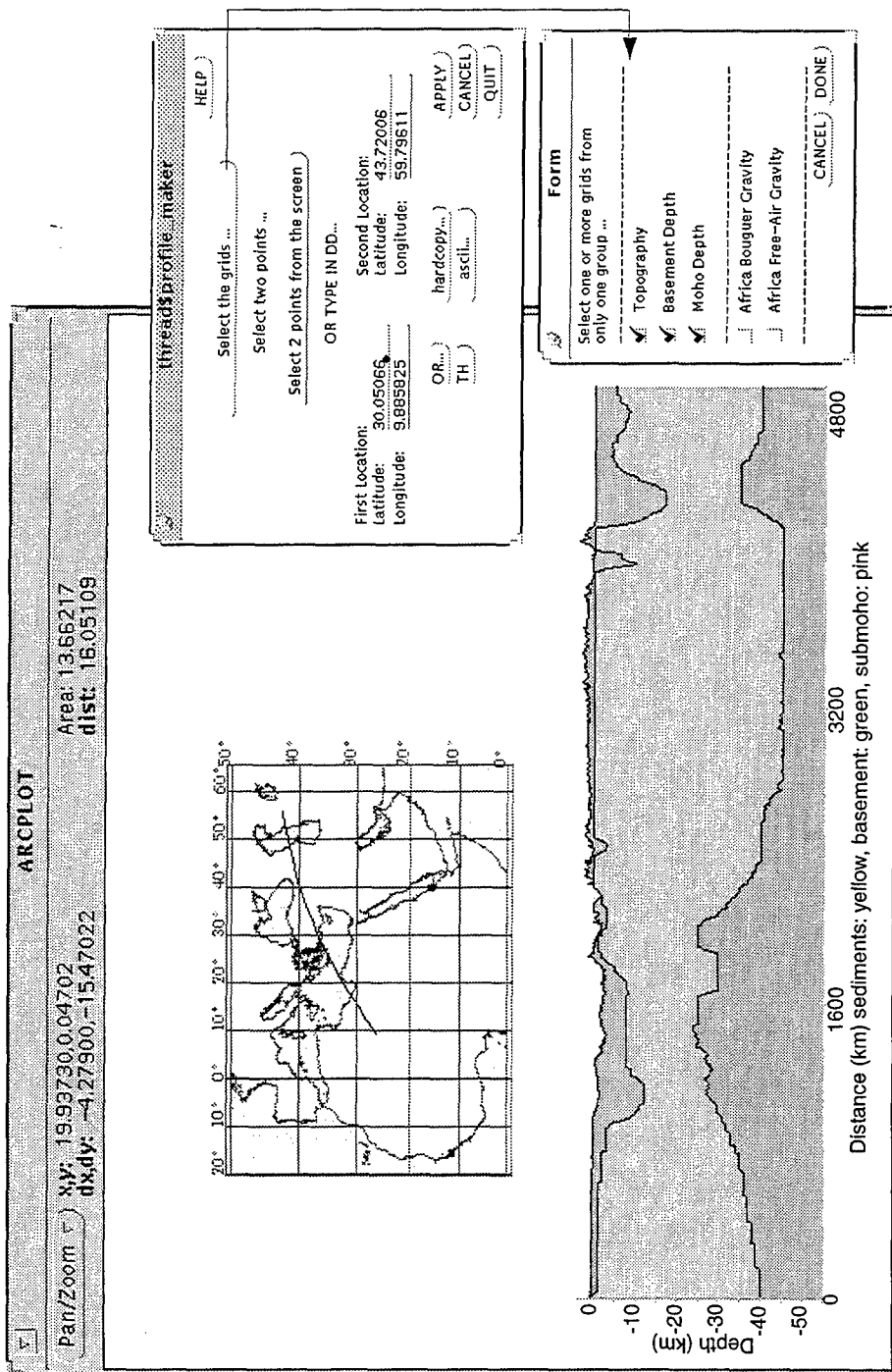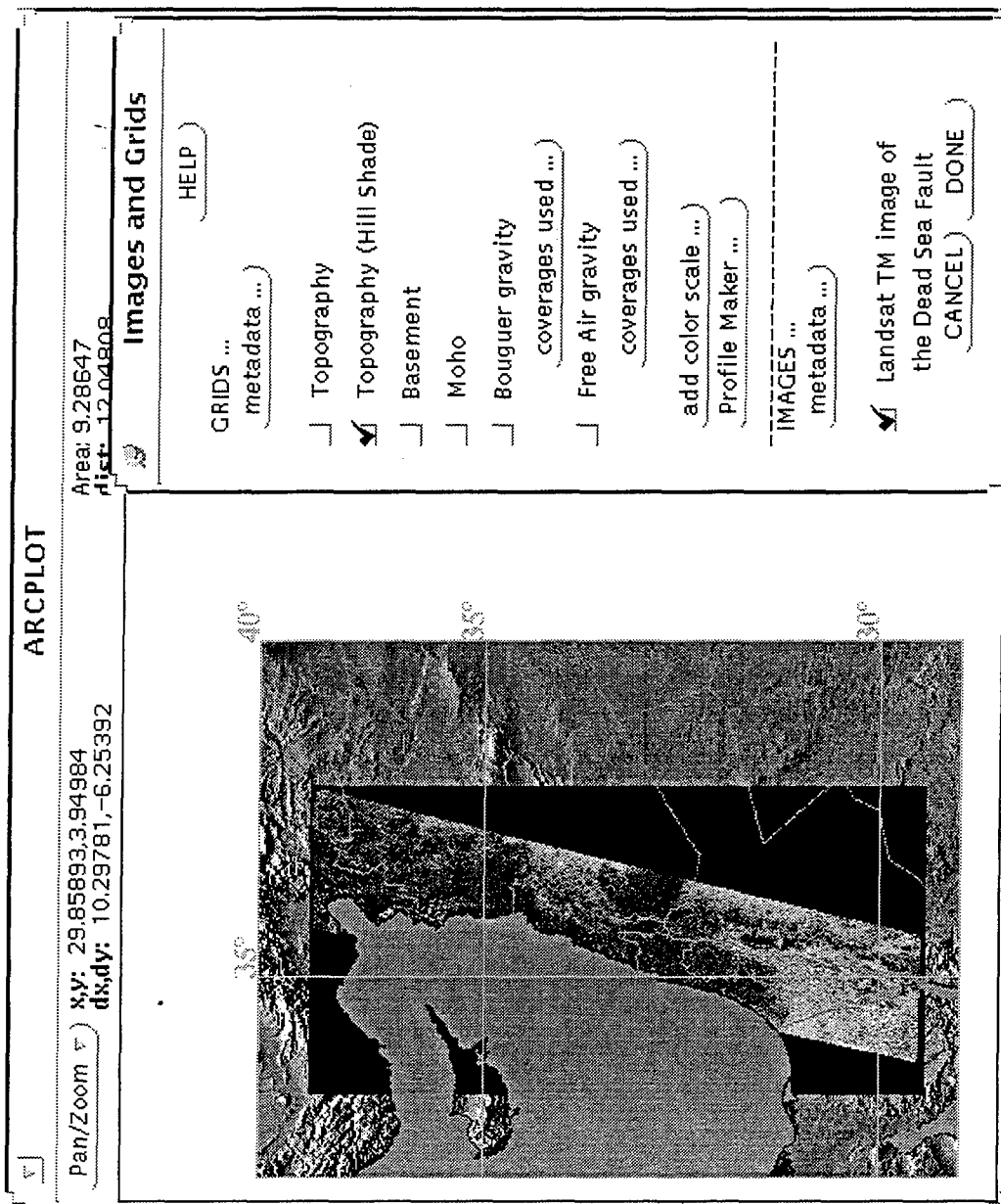
Figure 17

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Figure 18

```
┌─────────────────────────────────────────────────────────┐
│  ⨯        run_arcplot_command                            │
├─────────────────────────────────────────────────────────┤
│  Enter an ArcPlot command per line or run your own AMLS: │
│                                                          │
│  linecolor magenta                                       │
│  arcs data/egypt/mohodepth◈                              │
│                                                          │
│                                                          │
│                                                          │
│                                                          │
│              Clear command lines )                       │
│                                                          │
│          apply first │ apply last                        │
│                                                          │
│     WARNING: These commands will be included in hardcopies│
│     and so on, unless you delete them from here.         │
│                                                          │
│                   CANCEL )                               │
│                                                          │
└─────────────────────────────────────────────────────────┘
```

Figure 19

Redraw

The redraw button is used after some changes are made to display parameters. It automatically checks which options have been checked and re-reads the parameters then displays the requested data sets.

Line/marker/shade sets

This menu button is used to change default colors and line and shade colors, resizing the text, line thickness, point symbol and size (Figure 20). Before displaying the appropriate data sets colors and symbols can be selected for each data set, and then the data request button should be checked. The set values are permanent for the work session. Once the system is quit, these set parameters are lost.

Hard copy

This button is used to make a hardcopy of the screen. Most of the data sets can be plotted from this menu. A few others have their own hardcopy buttons that should be used for that specific purpose only. It is possible to make a Postscript, GIF, Illustrator, and CGM formatted hard copies (Figure 21). At this time the system allows only page size copies. In future releases hard copies based on map scales will be made available for larger maps. A user needs to define a directory path and a file name. Extension will be added according to hardcopy format selected.

2.1.5. Menu System Functions

Save algorithm and load algorithm buttons

These two menu buttons are used in saving a user environment, and loading it back to the system as needed (Figure 22). Save algorithm button is used once a user progresses in setting up data sets that are of interest, color and symbol sizes, map area. All these environment variables can be saved into a file that will be used at a later session. This allows to re-establish several pre-setup conditions with ease.
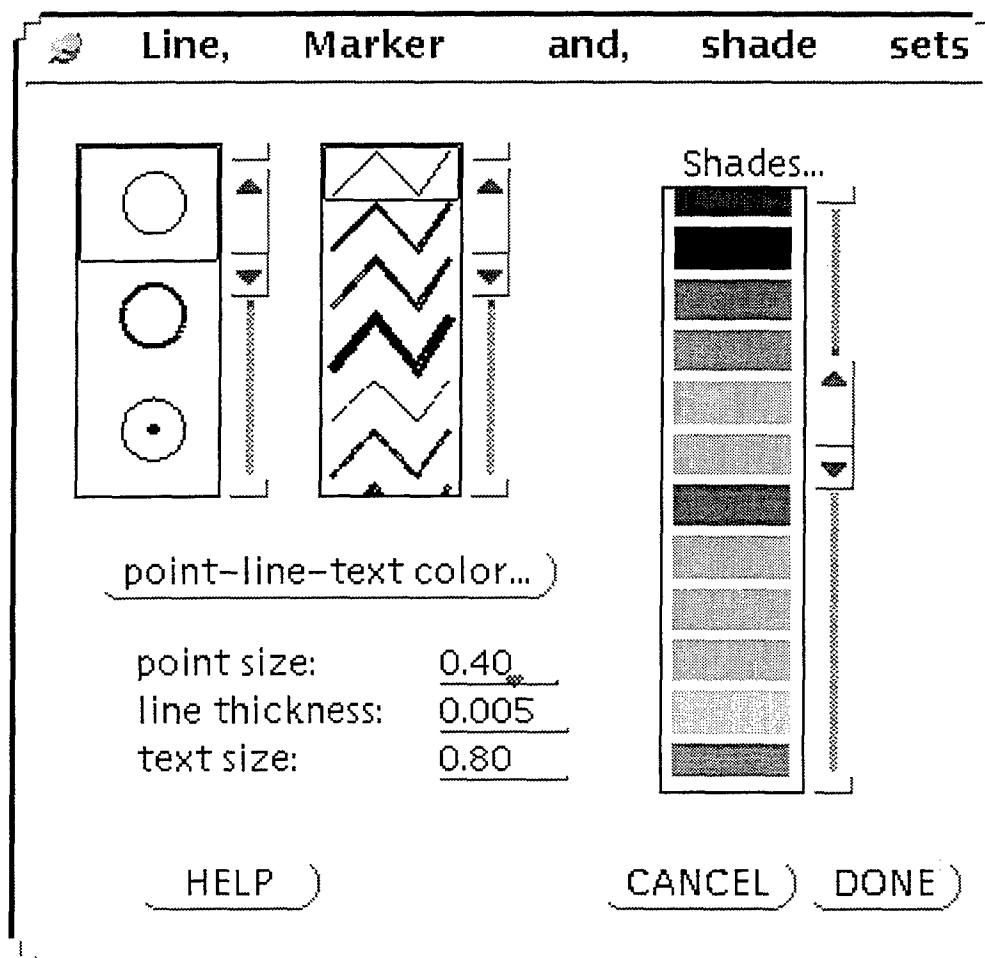
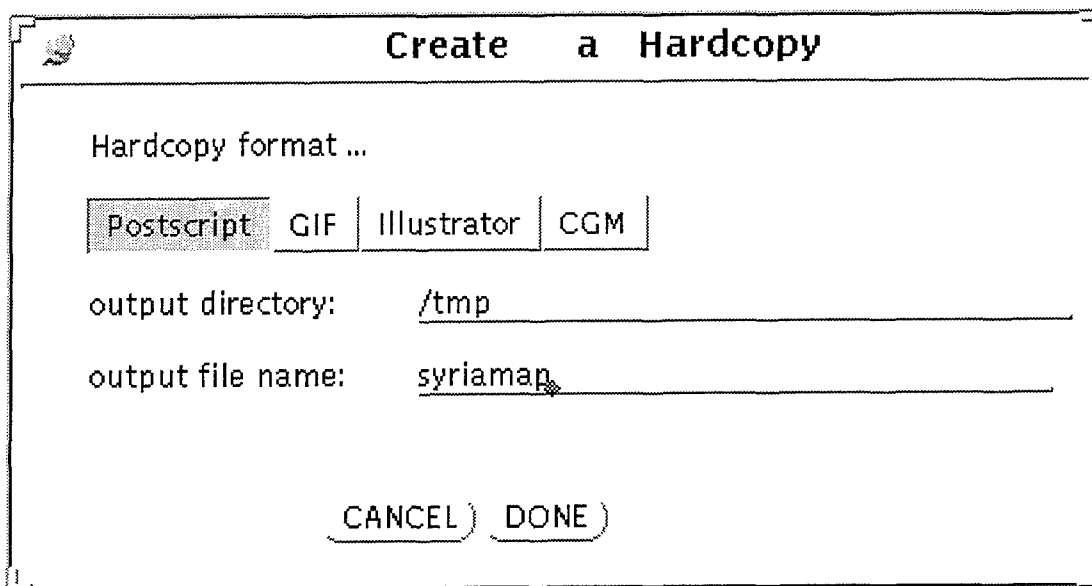**Line,   Marker   and,   shade   sets**

Shades...

point–line–text color...

point size: 0.40

line thickness: 0.005

text size: 0.80

HELP   CANCEL   DONE
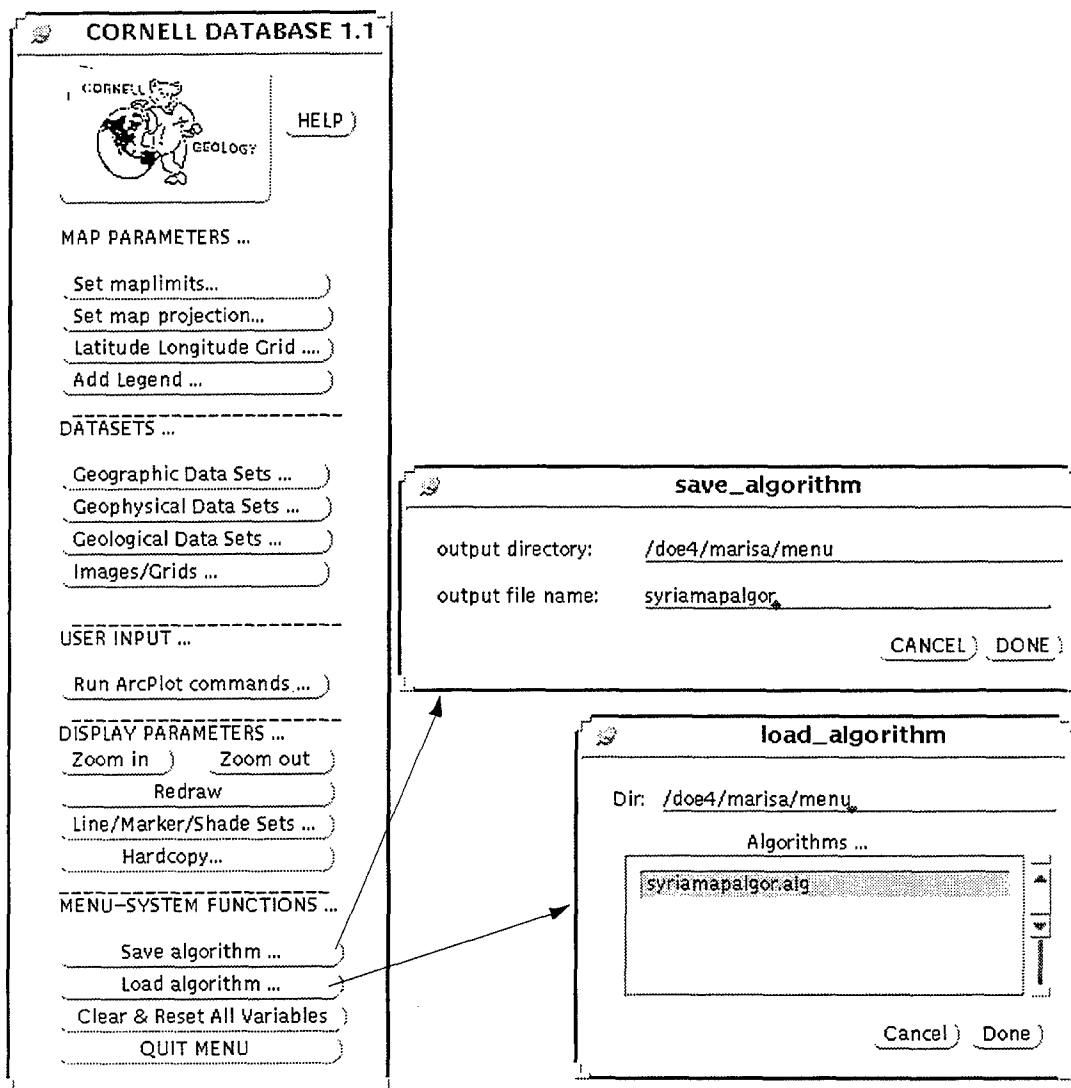
Figure 20

Figure 21

Figure 22

Clear & reset all variables

This button is used to refresh and re-establish the default variables.

Quit menu

This button terminates the whole session and exits from the databases.

2.2 World Wide Web (WWW) Access to Cornell Databases

Considering that access to ArcInfo software is not available for several research groups, we are also developing an ArcInfo - WWW interface to our developed databases. A prototype system is now available and functioning well. With this release we are switching our regular Web address and host computer from a shared system to a specifically designated computer with a new address. A SUN Ultra 1 server has been established to speedily serve data sets to CTBT researchers. Our new web address is "http://atlas.geo.cornell.edu"

Access to ArcInfo databases is provided through a specially designed programs. We are trying to keep the architecture in the Web pages as close to those in ArcInfo menu system as possible. Although this will not give as much flexibility in data manipulation, 80-90% of the menu driven functionalities available in the menu driven system will be accomplished under this system (Figures 23 and 24).

3. ORIGINAL RESEARCH IN SUPPORT OF THE MIDDLE EAST AND NORTH AFRICA GIS DATABASE DEVELOPMENT

Another essential component to our GIS development is the addition of new geophysical databases that we are incorporating into our GIS. The research we are pursuing is designed to address those regions and datasets that previously have not been investigated. We are presenting here three different areas of research that have helped make the information available in our GIS databases more complete.
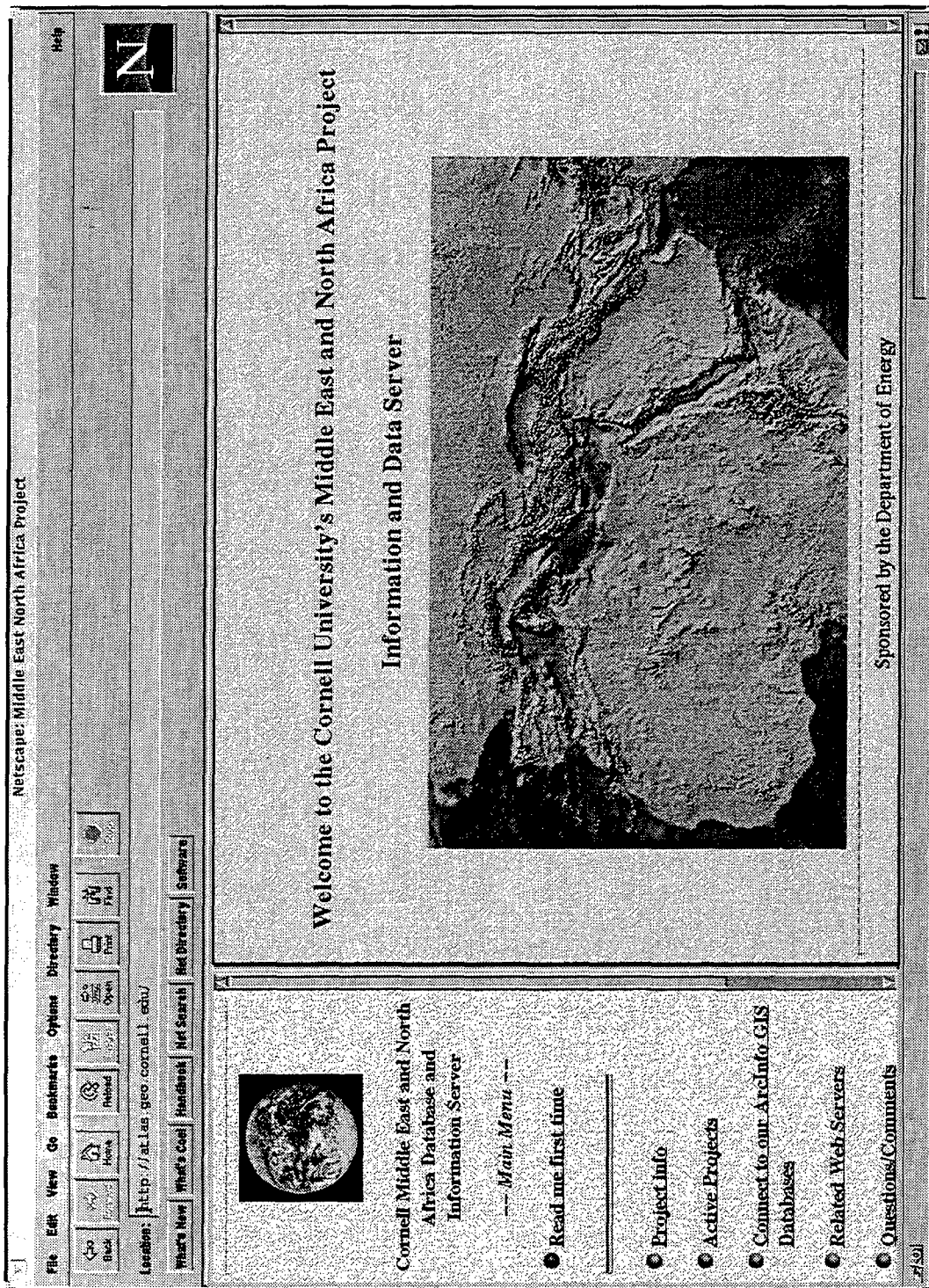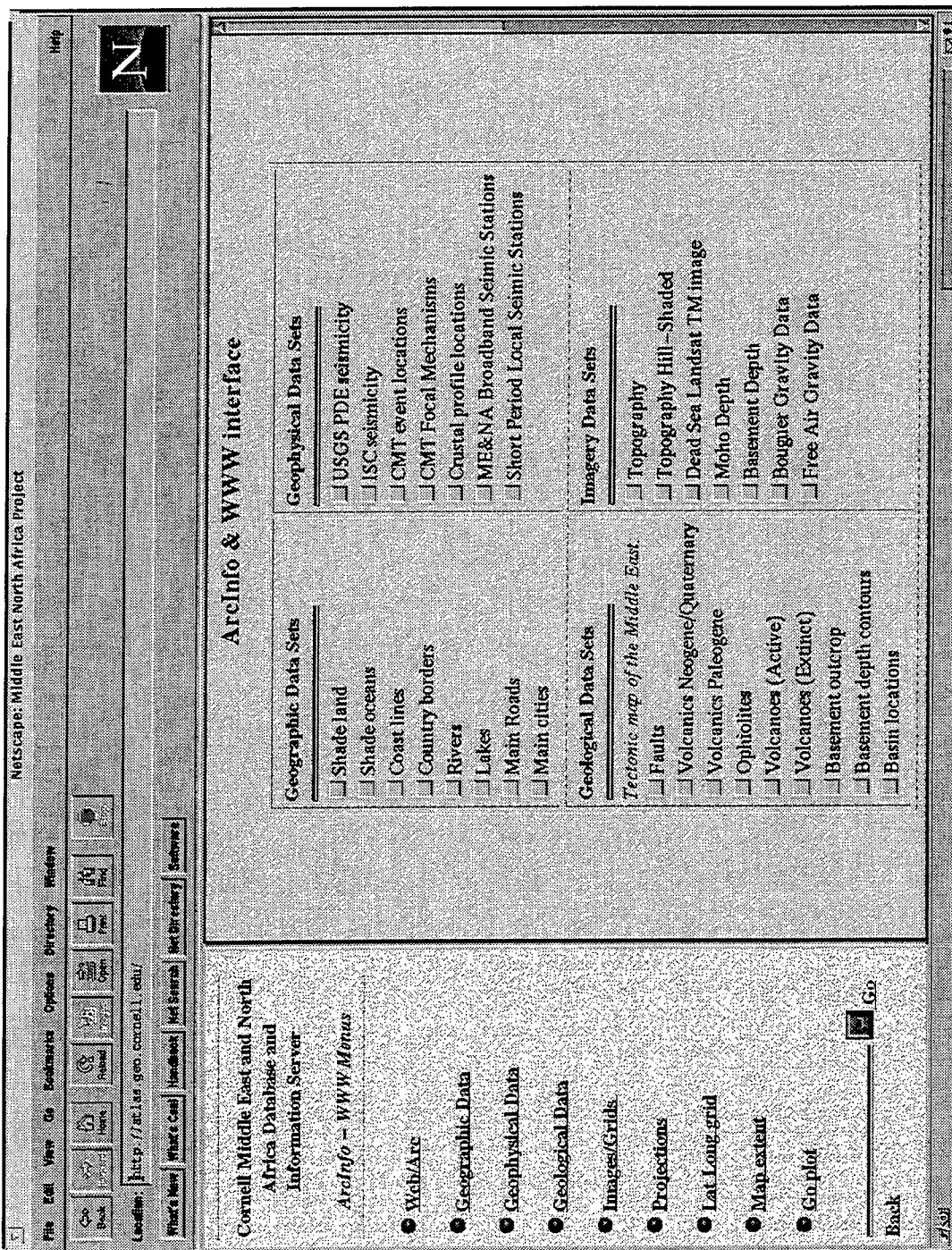
Figure 23

File Edit View Go Bookmarks Options Directory Window

Help

N

Location: http://at.as.geo.cornell.edu/

What's New | What's Cool | Handbook | Net Search | Net Directory | Software

Cornell Middle East and North
Africa Database and
Information Server

ArcInfo – WWW Menus

● **Web/Arc**

● **Geographic Data**

● **Geophysical Data**

● **Geological Data**

● **Images/Grids**

● **Projections**

● **Lat Long grid**

● **Map extent**

● **Go plot**

▓ Go

Back

ArcInfo & WWW interface

Geographic Data Sets

☐ Shade land
☐ Shade oceans
☐ Coast lines
☐ Country borders
☐ Rivers
☐ Lakes
☐ Main Roads
☐ Main cities

Geophysical Data Sets

☐ USGS PDE seismicity
☐ ISC seismicity
☐ CMT event locations
☐ CMT Focal Mechanisms
☐ Crustal profile locations
☐ ME&NA Broadband Seimic Stations
☐ Short Period Local Seimic Stations

Geological Data Sets

Tectonic map of the Middle East
☐ Faults
☐ Volcanics Neogene/Quaternary
☐ Volcanics Paleogene
☐ Ophiolites
☐ Volcanoes (Active)
☐ Volcanoes (Extinct)
☐ Basement outcrop
☐ Basement depth contours
☐ Basin locations

Imagery Data Sets

☐ Topography
☐ Topography Hill–Shaded
☐ Dead Sea Landsat TM image
☐ Moho Depth
☐ Basement Depth
☐ Bouguer Gravity Data
☐ Free Air Gravity Data

Figure 24

34

3.1 Discrimination of Chemical Explosions in Morocco

3.1.1 Introduction

To examine the limitations in the techniques for discriminating between chemical explosions and earthquakes at local and regional distances, we have applied several standard heuristics to seismic events in northwest Morocco where little *a priori* information was available. Although the 8 Oud Zem phosphate mine explosions (see Figure 25) have similar geographic locations, total charge magnitudes, and presumably ripple fired mechanisms, the seismic recordings are characterized by a surprising amount of diversity. Time and path independent modulations, owing to the periodic source mechanism of the ripple fired explosions, rarely unequivocally distinguish the explosions from the earthquakes. Our findings imply that more often than the current literature suggests, source inconsistencies have a role in the failure of common discriminants. Furthermore, crustal seismic velocity and the attenuation structure seemed to shape the seismic signals more than the nature of the source mechanism. The 10-15 Hz Pg/Sg ratio test proved to be the most precise and accurate discriminant. Finally, we argue that a regional case-based approach requires extensive regional information to meet the demanding verification goals of the proposed Comprehensive Test Ban Treaty.

Large industrial explosions for mining and excavating are almost always chemical explosions which can be as large as 500 metric tons (Smith, 1989). Usually chemical explosions over a few tons are actually a series of time-delayed sub-explosions, or *ripple fired explosions*, whose spatial and temporal layout are determined by the purpose of the explosion, the topography, and the equipment available for the blasts. The source multiplicity inherent in ripple fired explosions is often the characteristic used to discriminate large chemical explosions from nuclear explosions and earthquakes (e.g., Baumgardt and Ziegler, 1988; Smith, 1989; Kim *et al.*, 1994). Various compressional and shear wave ratios (amplitude and spectral) have been used to discriminate between all types of explosions and earthquakes, in an attempt to apply the basic physical conclusion that explosions excite more compressional waves than earthquakes relative to shear waves (e.g., Pomeroy *et al.*, 1982; Taylor *et al.*, 1989; Kim *et al.*, 1994; Walter *et al.*, 1995).
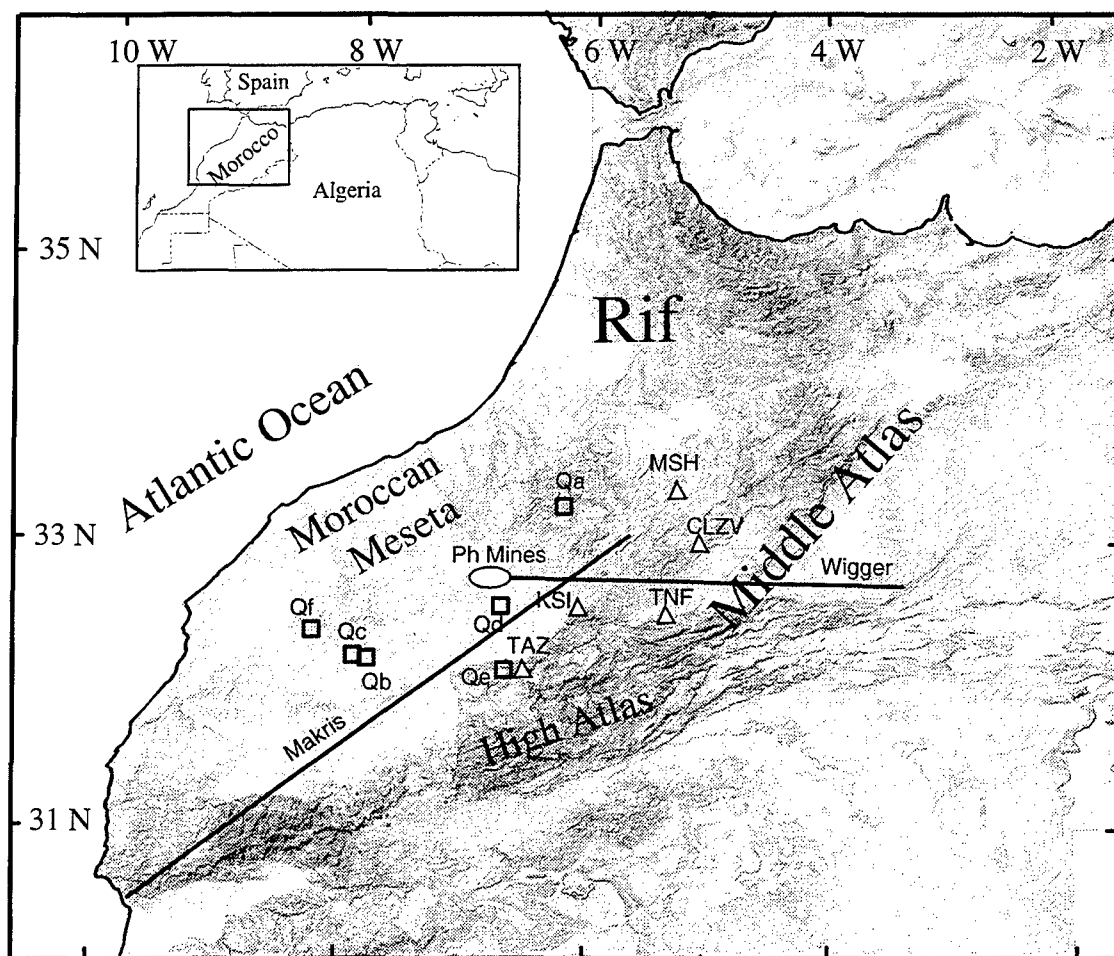
Figure 25

This study applies many of the techniques and tools mentioned above to a new geologic setting, Morocco, under less favorable circumstances. The constraints and limitations of spectral discrimination techniques will be qualitatively explored by examining source and path effects. Also, some of the previously cited discrimination methods will be employed in an attempt to develop a systematic discriminant that minimizes case-by-case analyses. To some extent, our study can serve as an assessment of current discrimination techniques in a complicated world of inadequate information. Attention will be paid to failures, particularly when those failures could be a result of geologic conditions, such as crustal structure.

The seismic events and stations used in this study are located in northwest Morocco (Figure 25). The collision of the African and Eurasian plates governs Morocco's geomorphology (e.g., Jacobshagen *et al.*, 1988). The Atlas mountains of Morocco are an active intracontinental mountain system composed of two inverted Mesozoic rift systems: the High Atlas that runs approximately east-west, and the Middle Atlas that trends northeast and merges into the interplate Beltic-Rif mountain system.

Although most refraction velocity profile data for the Moroccan crust and uppermost mantle are not well established, two studies provide pertinent, but approximate, profile information about the two paths. The Makris *et al.* (1985) profile (labeled "Makris" in Figure 25) showed that the direct P-wave travels at a velocity of 5.5 km/s and is finally overtaken by Pg after nearly 40 km at an apparent velocity of 6.0 km/s, because the thickness of the sediments is almost 4 km and the velocity contrast is small. The Pn velocity is somewhat slow at 7.8 km/s and does not appear as the first arrival until approximately 140 km, if it can be seen over the background noise. Also, Makris *et al.* found an Sg apparent velocity to be approximately 3.3 km/s homogeneous along the profile, and the Moho to be about 30 km deep. Wigger *et al.* (1992) found from their profile (labeled "Wigger" in Figure 25) the Moho's depth to be approximately 35 km with an average Pn velocity at the uppermost mantle of about 7.7-7.9 km/s, also relatively slow, as was found in the Makris *et al.* profile. They also determined that the maximum thickness of the crust was under the northern border of the High Atlas at 38-39 km.

3.1.2 Data

The Oud Zem phosphate mines in the Moroccan Meseta provide an opportunity to analyze recordings produced by ripple fired explosions significantly

different than those already noted in the literature (Figure 25). After subjecting all available explosion seismograms to a number of tests, the explosion population was trimmed down to 8 explosions (labeled Xa through Xh) with a total of 33 recordings. Because of both their total charge magnitude and their presumed purpose (phosphate surface mining), the explosions are assumed to be ripple fired. Spatial-temporal layout data independent of the seismic analysis were not available.

Although the orogenic regions of Morocco are seismically active, the same cannot be said of the Moroccan Meseta near the phosphate mines. After searching through a database of hundreds of recent Moroccan seismic events, only 6 (labeled Qa through Qf) events were found that might have similar propagation paths as that of the explosions. After subjecting the seismograms of these events to a number of tests like those of the explosions, the record population was reduced to only 13 recordings. Each of the non-Oud Zem phosphate mine events were located usually using about 5 or 6 recordings. Owing to typical errors found in hypocenter inversions, the locations could vary by several kilometers. Finally, not all of the seismic events (labeled as earthquakes) are necessarily earthquakes. Qb and Qc are located near a region known to have had phosphate mines at one time, but they are not located on the active phosphate mines themselves. The origin times of Qb and Qc are both in the early evening. Most of the known explosions, however, were blasted in mid-afternoon. Qd is most certainly an explosion, but it is still not labeled as such since it cannot be independently confirmed as an explosion. It is located near the phosphate mines, but once again it is not on the known mines themselves. The Qd origin time is in mid-afternoon, prime time for the explosions.
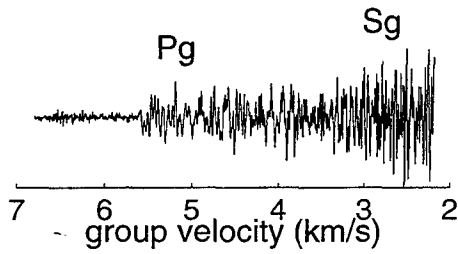
3.1.3 Processing Methods

Only short period seismic stations with 1 Hz geophones that recorded both earthquakes and explosions in proportionate numbers were included in the analysis in order to control for station effects and thus to allow direct comparisons between events. Recordings that have under a 2:1 rms signal to noise ratio were eliminated from the population. These two tests eliminated over 50 recordings for the events and disqualified 6 other events completely.

The seismic recordings of the 8 Oud Zem phosphate mine explosions were characterized by a surprising amount of diversity in view of their similar purpose, total charge magnitude, ripple-fired mechanism, and location. While phase and path independent spectral scalloping were noticeable in many of the signals to some
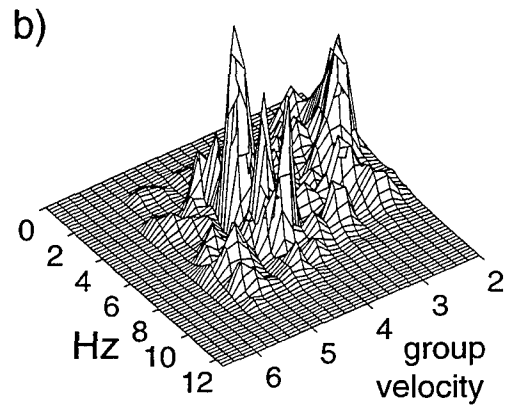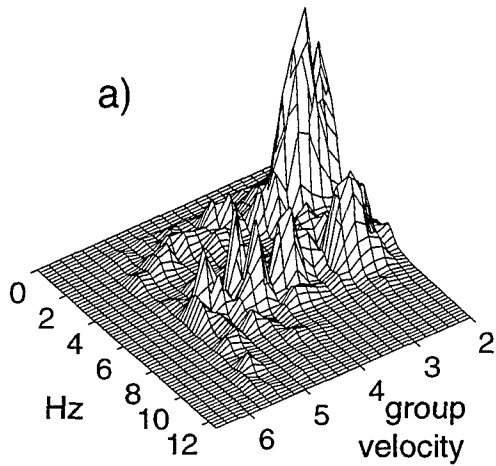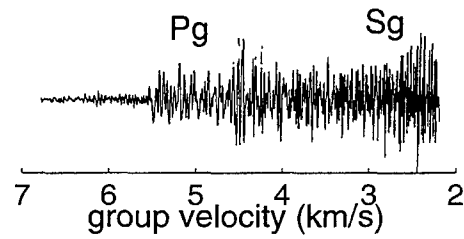
extent, those features were hardly ubiquitous. Furthermore, among the signals for which spectral modulation was clearly evident, the frequencies of their maxima and minima were not related, even for those cases where the propagation path, recording station, and total charge size were similar. These observations suggest that the spatial-temporal arrangement of the source varied considerably, whether intentionally as a result of blast requirements or crew preferences, or as a result of misfirings. For example, Figure 26 shows the seismograms and velocity-frequency distributions for two explosions, Xa and Xb, both comparable in magnitude and both exploded at the Oud Zem site. The signals shown in Figures 26a and 26b are recorded by the same seismograph station, KSI. Explosion Xa is much more coherent and impulsive than explosion Xb. From Xa's spectrogram, two phase independent modulations can be noted, one at about 3 Hz and the other at about 7 Hz. From Xb's spectrogram, any phase independent modulations are not obvious (the vertical scale of the spectrogram is linear, so possible scalloping at higher frequencies is obscured). The destructive interference apparent in Xb's spectrogram could be the result of a second blast bench, if it is significant in charge size in relation to the initial rippled-fired blast. This hypothesis is supported by a large arrival on Xb's seismogram just after the section labeled Pg (in accordance with the Pg velocity window established from the first motion). The brief listing for Xb in the blast log only notes one blast bench, however. This abnormality is one of the more conspicuous variations among the observed ripple fired source mechanisms.

Surficial features such as topography seemed to affect the seismic signals. Figures 26c and 26d are the recorded signals of explosions Xa and Xb, respectively, at station TNF (Figure 25). The recordings' back-azimuths to the location of the explosions are comparable to those at the KSI station. The seismic signals from explosions Xa and Xb are similarly filtered presumably by their propagation through the Middle-High Atlas junction. The Sg phase is much more attenuated than the Pg phase. The resulting spectrograms are dramatically different than their counterparts constructed from the signals recorded at the KSI station. Note that at this distance, the consequences of that postulated second blast bench to the velocity-frequency distribution are minimal. Explosion Xa's spectrogram, Xa's modulations are much more prominent than those of Xb. The phase independence of Xb's scalloping is still not apparent.
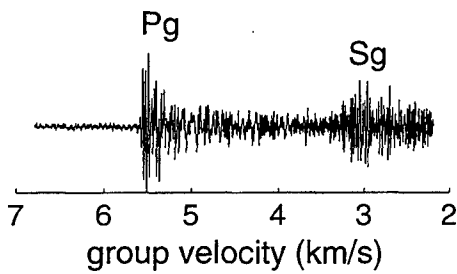
Xa-KSI (dis=72km, baz=288°) Xb-KSI (dis=76km, baz=285°)

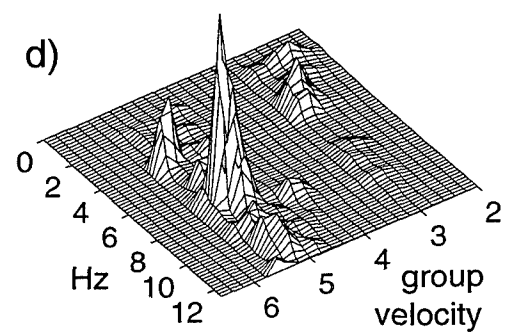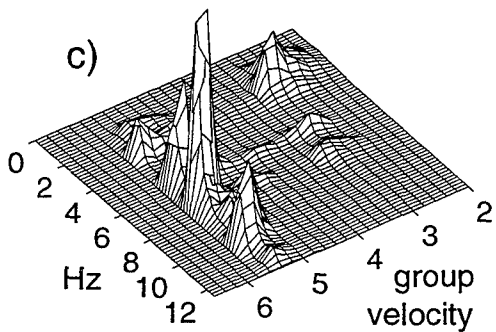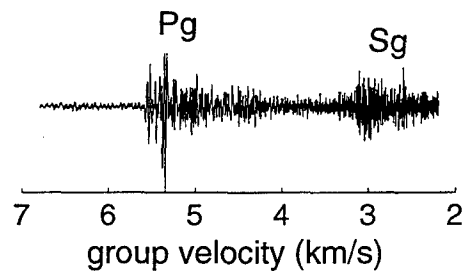Xa-TNF (dis=138km, baz=281°) Xb-TNF (dis=143km, baz=280°)

Figure 26

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Propagation effects concealed differences between the seismic signals of explosions and earthquakes. An explosion and earthquake which were quite distinguishable at one station (whose back-azimuth and distance to each event were similar), were in some cases much less distinguishable by recordings at other stations. A representative case is that of explosion Xb and earthquake Qe. For both events the Pg and Sg amplitudes recorded at MSH are of the same order of magnitude, and the energy of the phases is distributed similarly in frequency space. The explosion's Pg / Sg ratio is larger than that of the earthquake, and more of the explosion's energy spills over into higher frequencies. A comparison of explosion Xb's recording at MSH with that at KSI and TNF shows the importance of azimuthal and propagation effects, as well as highlights the similarities between Xb's and Qe's signal at MSH. As seen in Figure 26, the scalloping of the explosion signal is relatively consistent for the lower frequencies inside of two path groups, that of CLZV and TNF, and that of KSI, MSH, and TAZ. Above 8 Hz, the frequency maxima and minima within these groups no longer correlate. As in Xb's case, for Qe's power spectra the lower frequency maxima and minima of CLZV and TNF correlate. Because of the above similarities, it is difficult to recognize path independent modulations for one power spectrum and not the other. These observations indicate that path dependencies, rather than source characteristics, seem to dominate the signal's form.

As discriminants, the most successful ratio tests were the 5-10 Hz Pg / 5-10 Hz Sg and 10-15 Hz Pg / 10-15 Hz Sg spectral tests (Figure 27). The variance in the performance of both tests, due to differences in the recording station, was still considerable. The spectral ratio tests within phases (e.g., 1-2 Hz Sg / 6-8 Hz Sg) were unable to separate the explosions from the earthquakes. The Pg/Sg maximum amplitude test was also ineffective. Any first order dependency on propagation distance was removed from the ratios with a linear least squares fit. The discriminant line was rather arbitrarily chosen as the median value of the earthquakes. The authors are aware of statistical methods for selecting the discriminant line (e.g., Elvers, 1974; Taylor *et al.*, 1989; Woodward and Gray, 1995), but as will be explicated below, our small and uncertain training set does not warrant such approaches. If the two spectral discriminants are integrated by a union (*vis-a-vis* intersection) and seismic information from only a single station is available, then a single explosion recording has a 12% probability of being classified as an earthquake, and a single earthquake recording has a 23% probability of being classified as an explosion. If all of the recordings of an event are used in the discrimination scheme (a networked system), then only "earthquake" Qd would be "missclassified." As already mentioned
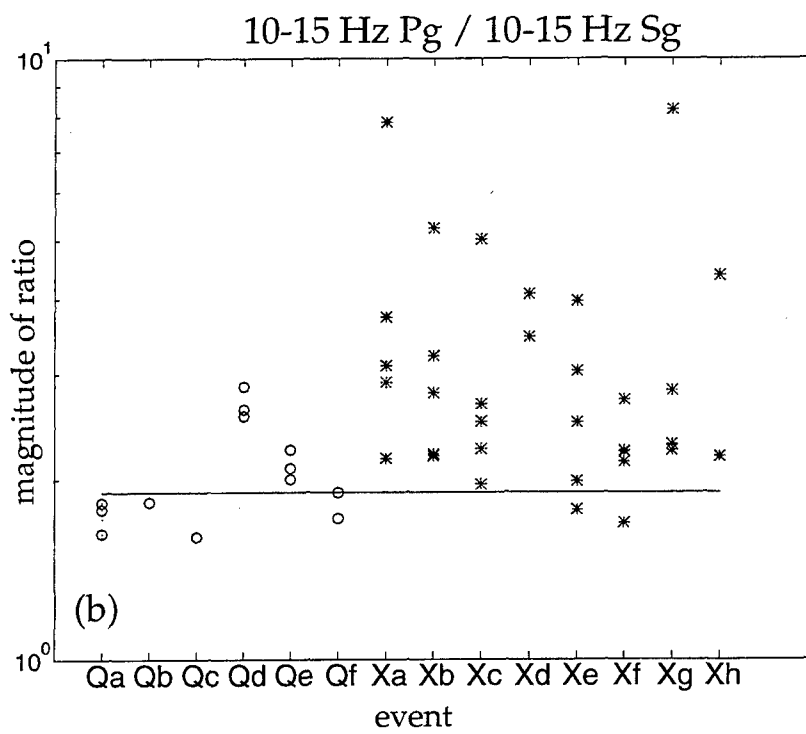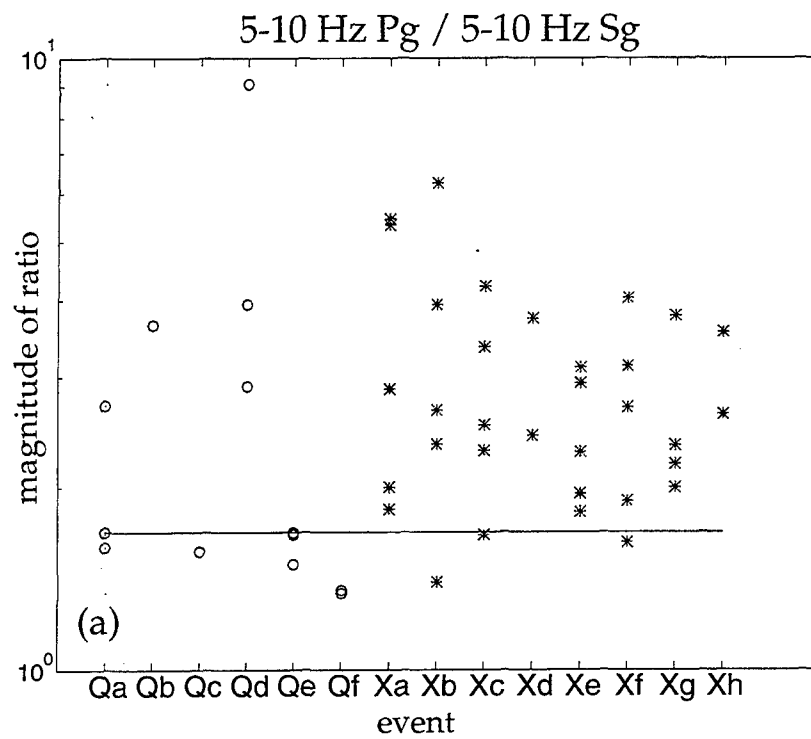
41

Figure 27

in the *Data* section, judging from *a priori* information such as origin time and location, event Qd is most likely an explosion and not an earthquake (but independent confirmation is not available through blasting logs, etc., so the event is assumed to be an earthquake). If Qd is considered an explosion in the training set, then the network approach would classify every event correctly. Thus, since the original discriminant is based on a flawed training set, its results represent a worst case scenario which reflects some of the challenges of constructing a discriminant in a world of uncertain and incomplete information.

3.1.4 Discussion and Conclusions

The large regional variability of source mechanisms, source geologic conditions, and propagation paths and the geophysical and seismological community's relative lack of a comprehensive physical understanding of propagation effects, have encouraged site-dependent, case-based approaches for discriminating between earthquakes, industrial explosions, and nuclear explosions. As shown by our study, the empirical heuristics utilized in case-based approaches have limitations that must be considered by any CTBT verification system.

Our findings argue that more often than the current literature suggests, source inconsistencies may result in the failure of time independent spectral modulations to discriminate between earthquakes and ripple-fired explosions. Specifically, we agree with the observations of Baumgardt and Young (1990) and Kim *et al.* (1994) that for some ripple fired explosions time independent spectral modulations may or may not exist, and that if they do exist, they need not be consistent among different explosions, even if those explosions originate from the same mine or quarry. Irregular source delays have been noted elsewhere (e.g., Richards *et al.*, 1991). As our results imply, the inability of time independent modulations to discriminate between earthquakes and explosions may not necessarily be the exception.

Low frequency path independent modulations advocated by Gitterman and van Eck (1993) also can be inconclusive for discrimination purposes, possibly as a result of the spatial-temporal layout of the explosion, the earthquake mechanism's radiation pattern, or disproportionate phase attenuation. We found that the travel path through the Middle-High Atlas junction significantly attenuates shear waves (in our case, Sg) with respect to the compressional waves. This observation agrees with, for example, the Kim *et al.* (1994) finding that Lg propagation was disrupted when significant structural variations were encountered, such as in their case the

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Appalachian platform in southern New York-New Jersey. We also found that in the low frequencies, earthquakes often seemed to demonstrate path independent spectral modulation similar to that of ripple fired explosions; at higher frequencies, the scalloping from ripple fired explosions was often incoherent among recording stations. As in the case of time independent modulations, path independent modulations might exist for a significant portion of the ripple fired explosion recordings, but they might not be conclusive enough in comparison to earthquake power spectrum data to use consistently and reliably as a discriminant.

Our attempts to discriminate between earthquakes and explosions using spectral ratios confirm several findings in the literature. As noted by Baumgardt and Young (1990), for separating ripple fired explosions from earthquakes the P/S spectral discriminants seem to perform considerably better than spectral discriminants within the same phase. This directly contrasts with efforts to discriminate between nuclear explosions and earthquakes in the Western United States (Bennett and Murphy, 1986). The Walter *et al.* (1995) analysis suggests that this difference is not due to differences in source mechanism or tectonic paths, but to the source medium. We, however, observed that path propagation will make a significant difference in the discriminant's value. For example, the TNF station recordings usually had the highest Pg/Sg values. This dependency on propagation path agrees with the findings of Lynnes and Baumstark (1991) for P/S discriminants for Nevada Test Site explosions. Also in agreement with Richards *et al.* (1991) and Blandford (1995) our highest frequency P/S discriminant was our most successful ratio test. Finally, as Wuster (1993) has emphasized, empirical discriminants are fundamentally limited by their training sets. No doubt, this caveat is especially applicable for our relatively small data set.

This study applied many of the standard methods for discriminating between earthquakes and ripple fired explosions to a new geologic setting, northwest Morocco, in an effort to examine the limitations of these techniques. We found that although time and path independent spectral modulations can be useful, they are far from ubiquitous. Source mechanisms for explosions may vary substantially even among events from the same quarry or mine. Furthermore, crustal structure determines the character of the seismic signal to a greater extent than the source mechanism. Despite the susceptibility of spectral discriminant values for a given event to propagation effects, we were able to construct a discrimination technique that could systematically discriminate the events in our data set. The training set,

however, imposes fundamental constraints, especially since nuclear explosions are not constituent of that data set.

Since the source and path effects noted in this study are likely to play a role in all efforts to seismically discriminate among nuclear explosions, chemical explosions, and earthquakes, databases that organize regional geological, geophysical, seismological, and crustal information are critical components to the success of any seismic CTBT verification project. By recognizing the complexity of seismic discrimination, our study emphasizes that the regional case-based approach which has shown much promise requires nothing less than the best empirical information.

3.2. Upper Crustal Seismic Velocity Structure in Eastern Syria

3.2.1 Introduction

We present the interpretation of seismic refraction data collected along a north-south profile across the Euphrates depression and other zones of structural interest in eastern Syria (Figure 28). The results from refraction data are refined and supported by additional information from well-logs, seismic reflection and gravity data. The interpretation of these data is used to establish metamorphic basement depth in eastern Syria. This, along with indications of basement and deep sedimentary structure in the area, can help to better understand regional wave propagation and to better locate and calibrate regional events.

Eastern Syria is situated at the northern end of the Arabian platform which is believed accreted from several discrete continental blocks during the Proterozoic (e.g. Pallister et al., 1987; Stoesser & Camp, 1985). Suture zones corresponding to this accretion have been documented in the Arabian shield where basement rocks are exposed (Stoesser & Camp, 1985). Although it is reasonable to suppose similar sutures exist in the northern part of the Arabian platform (Barazangi et al., 1993; Best et al., 1990; Best et al., 1993), their location is difficult to ascertain because of thick sedimentary cover across much of the region. It has been suggested that the major present-day structural features of Syria are products of reactivation along these sutures which act as zones of weakness in the platform (Best et al., 1993; Litak et al., 1996a; Stoesser & Camp, 1985). Although an appreciable amount of research has been conducted in the Palmyride mountains of western Syria (e.g. Al-Saad et al., 1992; Barazangi et al., 1992; Chaimov et al., 1990, 1992), relatively little work has focused on eastern Syria. In particular, the Euphrates depression has received limited attention in
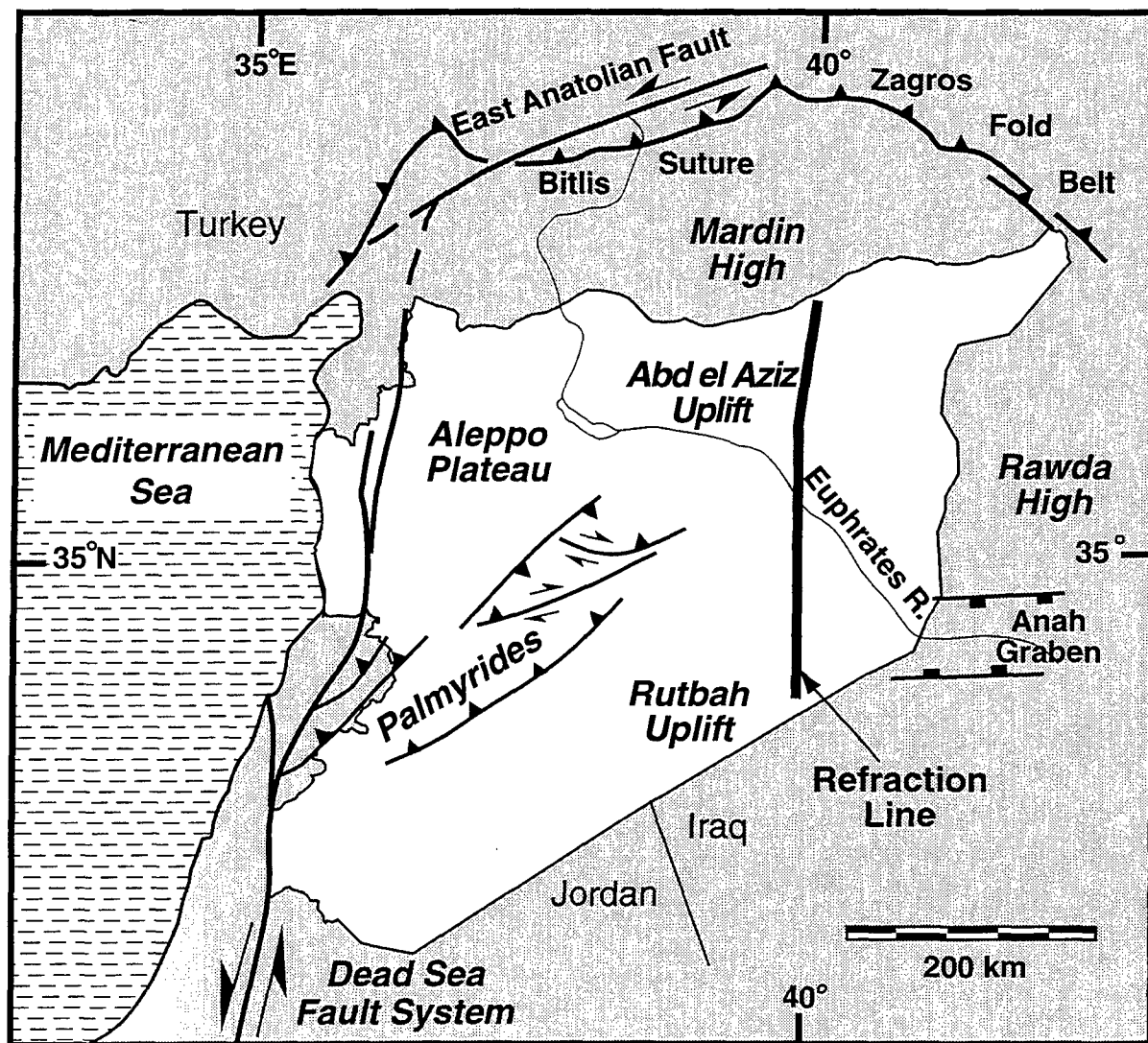
Figure 28

comparison to its geologic and economic importance (de Ruiter et al., 1994; Lovelock, 1984). Recent work (Alsdorf et al., 1995; Litak et al., 1996a; Litak et al., 1996b; Sawaf et al., 1993) has increased understanding of the Euphrates system but detailed assessment of basement structure and depth in eastern Syria has hitherto been unavailable.

The lack of constraints on basement depths in Syria is a consequence of an almost complete absence of basement outcrops and well penetration. Leonov et al. (1989) constructed a depth to basement map within Syria and established the broad trends which are still generally accepted although new results presented herein disagree somewhat with this earlier assessment. Seber et al. (1993) used refraction data to establish basement depths in western Syria and determined seismic velocity of the basement to be ~6 km/s. However, the lack of previous investigations in eastern Syria means that the results presented here significantly further current knowledge.

3.2.2 Method

The model of basement depth and deep sedimentary structure developed herein relies on the analysis of several data sources, particularly a high density seismic refraction line. The refraction data was collected as part of a larger seismic profiling effort spanning all of Syria conducted in 1972-3 (Ouglanov et al., 1974). Figure 28 shows the exact location of the refraction line which is 302.2 km long oriented essentially north-south. In total data from 23 shots, each with forward and reverse geophone spreads, are used here yielding a fold of coverage of at least 700% in most places.

After digitization of first arrivals from the original records, the refraction data were interpreted using a ray-tracing approach utilizing the software of Luetgert (1992). In an initial interpretation the positions and velocities of various user-defined layers in the software were subtly altered until travel times of calculated ray-paths through the computer model matched those of the digitized observed arrival times. Although this approach naturally produced a model in agreement with the refraction data, the velocity interfaces in this model were found to be in disagreement with velocity boundaries observed in sonic logs and two-way travel times from seismic reflection data. The disagreement was largely a consequence of the limitations in the refraction method, in particular the inability to detect low-velocity layers which are clearly demonstrated by the sonic logs.

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However, the ambiguity of low-velocity layers can be eliminated if velocity information and/or reflection times are available from an independent source. Therefore, an interpretation strategy was adopted in which the refraction, reflection and well data were used simultaneously in the refinement of the velocity model thus establishing a model consistent with all available data. An initial model, based on reflection profiles and sonic logs, was refined through ray-tracing to improve agreement with the refraction data (Figure 29), with particular attention to ensure compatibility with the other data sets. Correlations using sonic logs and seismic reflection data were used to guide modeling of the refraction data.

The modeling effort culminated in the 'final velocity model' (Figure 30) which satisfactorily fitted all the available data. Velocities from sonic logs agreed with those in the model. Two-way reflection times to certain interfaces in the model corresponded to two-way times in numerous intersecting seismic reflection profiles. Observed gravity data (not shown here) were compared to the gravity signature of the refraction model with each velocity layer assigned a density and the analysis showed broad agreement between the two profiles. Above all, the calculated refraction arrivals agree to within acceptable limits with the measured arrival times.

Figure 30 shows that velocities generally increase with depth in the model (as found in the refraction modeling of Seber et al. (1993). However, some low-velocity channels are observed which are thought to be controlled by lithology. For example, the upper Paleozoic strata, which are predominately shales and sandy shales represent a low-velocity layer when compared to the overlying Triassic dolomites and anhydrites. Such low-velocity layers would not have been detected by the refraction data alone. Only through the use of independent sources of velocity data, such as the sonic logs and reflection data can these low-velocity zones be identified.

Despite direct evidence for the majority of the model, a few uncertainties remain. Some of the low-velocity layers are not detected by the refraction method, are not penetrated by wells, and are not located unambiguously by seismic reflection data. Thus, positions of parts of these layers are uncertain and shown in the figures with dashed lines. It is also not possible to get exact measures of the velocities of the low-velocity zones in some of these cases and so velocities have been given which are interpolations between known data. Additionally, the depth to basement in the far south of the model is only believed to be a minimum constraint. No refractions were observed in this part of the refraction line at velocities considered typical of those for basement rocks. It is believed this is because geophone spreads were too short to detect refractions from this depth; therefore, the depth to basement shown is a
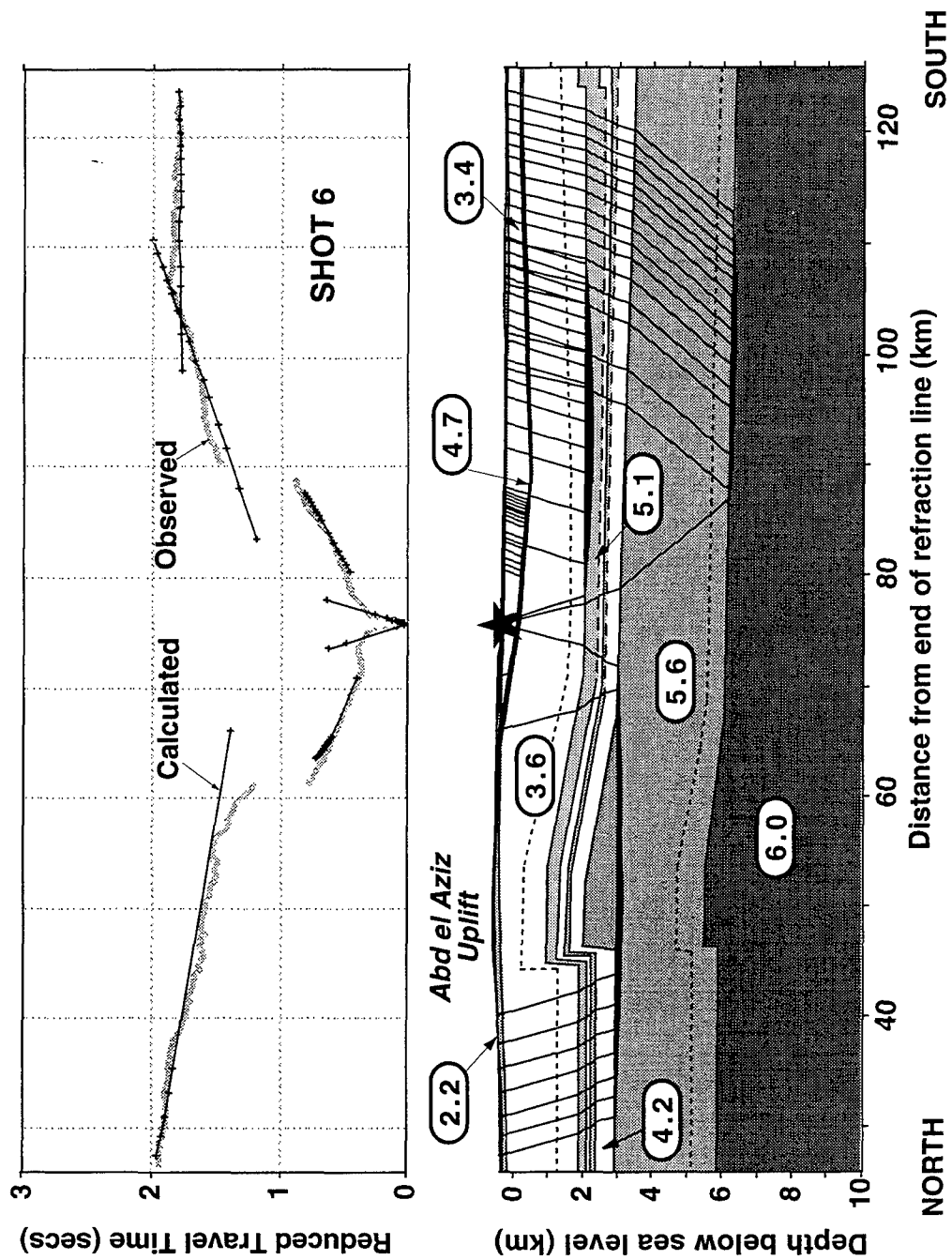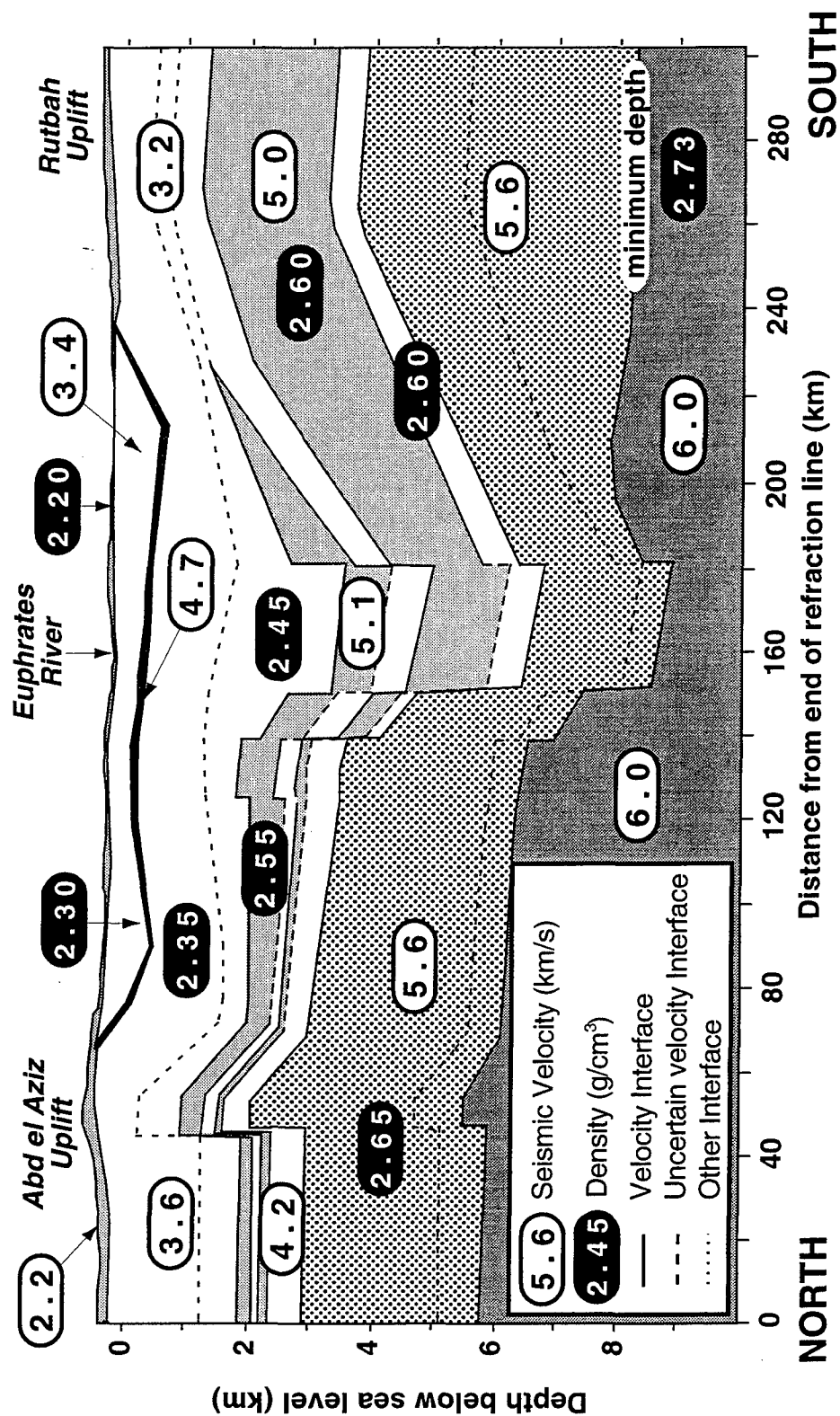
48

Figure 29

49

Figure 30

50

minimum (Figure 30). However, the majority of the final velocity model is based on direct evidence and the errors in the bulk of the model can be shown to be relatively small, with approximately ±200 m error on depth to most interfaces and ±0.1 km/s in velocities.

3.2.3 Conclusions

Basement depth beneath eastern Syria is found to be greater than previously supposed. In the south across the Rutbah uplift the basement is at least 8.5 km deep, in the Euphrates depression it is around 9 km, and to the north of the Euphrates basement is at about 6 km (Figure 30). Velocities of sedimentary formations are found to increase with depth and age although some low-velocity layers controlled by lithology are documented. The identification of these low-velocity zones would not be possible using the refraction data alone and only through the integrated use of several data sources can the low-velocity channels be unambiguously detected.

Deeply penetrating faults are identified in the Euphrates graben demonstrating the thick-skinned tectonic style of this region. Clearly different trends in basement depth on the northern and southern sides of the Euphrates graben could be further evidence for the Proterozoic accretion of the northern Arabian platform with the Euphrates system as a suture zone.

Our results significantly contribute to any modeling efforts to understand regional wave propagation in this critical area of the Middle East. Moreover, our accurate velocity determinations will improve event locations and calibrations.

3.3 Receiver Function Inversion in the Middle East and North Africa

3.3.1 Introduction

In the Middle East and North Africa there exist only a very sparse coverage of three-component broadband stations; therefore, we are limited in the types of seismological investigations we can employ. Hence, in order to obtain some idea of the velocity structure in this region we have used data from these stations to compile receiver functions, a single station method, for all broadband stations in the Middle East and North Africa. By inverting these receiver functions we hope to place some constraints on Moho depth's and average shear-wave velocities in regions where previously there has been very little information on crustal velocities and thicknesses.

We have chosen to only invert for first-order features in the crust and upper mantle in order to avoid over interpreting our receiver function data.

3.3.2 Data

We have collected over 600 Megabytes of broadband, three-component teleseismic waveform data from IRIS, MEDNET, GEOSCOPE and GEOFON broadband stations in the Middle East and North Africa (Figure 31). We have examined all of these records for good signal to noise ratios and eliminated those with signal to noise ratios of less than 5 to 1. We have also attempted to eliminate the effects of large scale lateral velocity heterogeneity by calculating the radial direction using the first motion of the teleseismic P-wave waveform. We have minimized the "corrected" tangential component and then rotated the horizontal components into these corrected radial and tangential directions. Although this procedure will not remove the effect of smaller scale crustal and upper mantle heterogeneity we have found that it does remove the effect of large scale mantle heterogeneity that can cause the teleseismic P-wave ray-paths to bend outside the great circle path.

We have employed the standard "water level" spectral division technique (e.g., Langston, 1979, Ammon et al., 1990) to calculate each of the receiver functions used in this study. In order to solve for receiver functions that are sensitive primarily to first-order features, we have used a guassian filter with an a = 1.5. This filter produced receiver functions that contained data with frequencies of .5 Hz and lower. From the 24 stations that we have collected data for, we have been able to calculate high quality receiver function waveforms for 12 stations (Figure 31).

3.3.3 Inversion Method

In order to invert the receiver function data for crustal and upper-most mantle shear-wave velocity structure we employed a grid search scheme using a maximum of six layers in our model. For simple receiver functions we used a one-layer crustal model (see stations BNG and DBIC in Figure 31) and still obtained a reasonable fit. The advantage of our grid search scheme, unlike other techniques, is the guarantee that we will solve only for global minima. We have used a grid spacing for the shear-wave velocities of 0.1 km/sec and a grid spacing for layer thicknesses of typically 2 km, and in some cases, 1 km for the first layer thickness. It is doubtful that with the
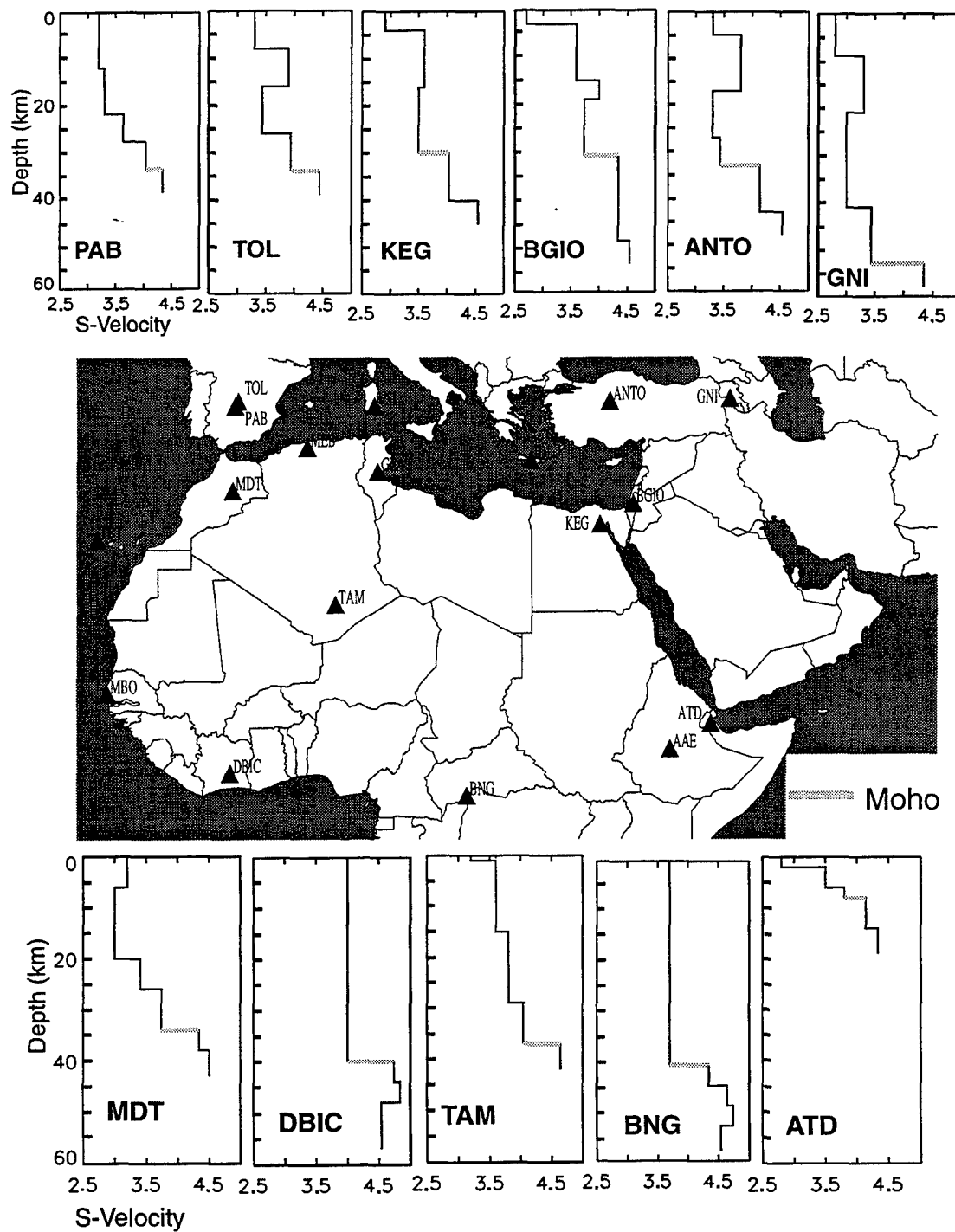
Figure 31

approximations we have made, that the receiver function inversion will be able to resolve model fluctuations smaller than these grid spacings.

By using only 10 model parameters (5 layers where we vary both the layer thickness and shear-wave velocity) in our inversion, the receiver function inversion's non-uniqueness problem is reduced. The longer period receiver functions are fit reasonably well by a 5 layer model (Figure 32). We also have been able to invert for a bulk Poisson's ratio for station's which only require 4 or less layers to model the receiver function waveforms. For example, at stations DBIC and BNG we have solved for a bulk Poisson's ratio of 0.25.

The grid search scheme allows us to map the RMS error surface. This allows us to examine for the possibility of non-uniqueness in our inversions. If multiple minima's exist within our error surface then our inversion results are non-unique. Figure 33 is a portion of the 9-dimensional error surface for station KEG in which we do not see evidence for large local minima which are located far from the global minima. However, this is only a portion of error surface from the grid search inversion. We are currently working a method in which we can estimate the noise contained within the receiver function which would then allow us to solve for a confidence region from our error surface.

We have found that comparisons between the grid search technique and the linearized least squares (LLS) method yield significantly different results if one does not consider the non-uniqueness of the LLS technique. For those receiver functions that are relatively simple in nature (i.e., only a P-to-S conversion at the Moho) then the results are similar. Figure 34 is an example of the difference given between these two methods. We have employed Ammon's et al. (1990) method of using multiple starting models (Figure 34).

3.3.4 Results

Crustal thickness in North Africa is found to be generally on the order of 38 to 41 km (see Figure 31) except station ATD which is located on exposed oceanic crust. We have found a Moho depth of 8 km for station ATD which is consistent with an oceanic crust. Data from three coastal stations in North Africa (MBO, TBT, and MEB) contain evidence of very strong lateral heterogeneity and teleseismic P-wave multipathing. In the Middle East, our estimated crustal and basement thicknesses compare well with the available seismic refraction profile interpretations. There is some ambiguity in where to interpret the Moho for station KEG's shear-wave velocity
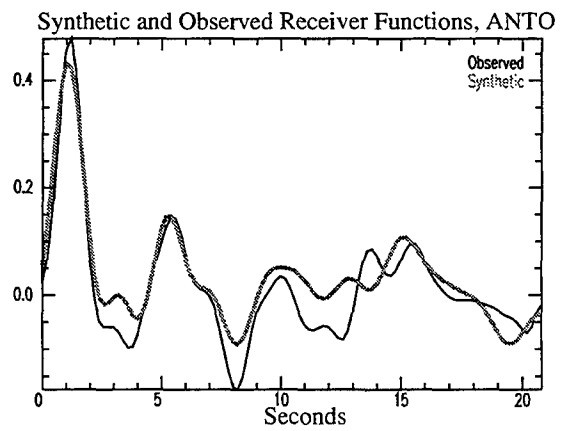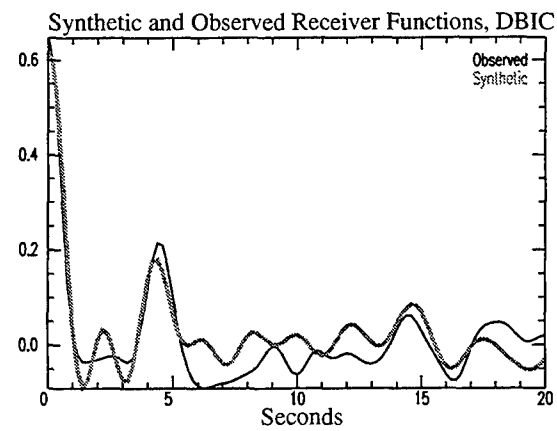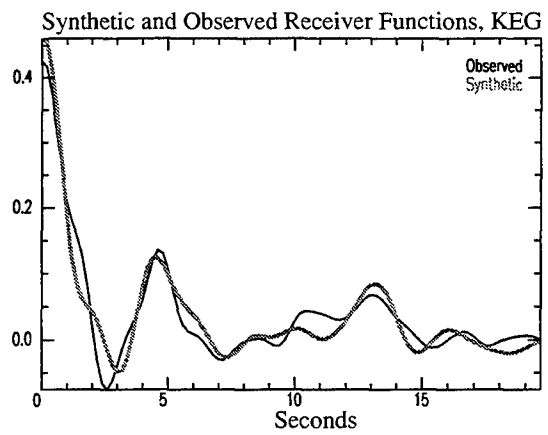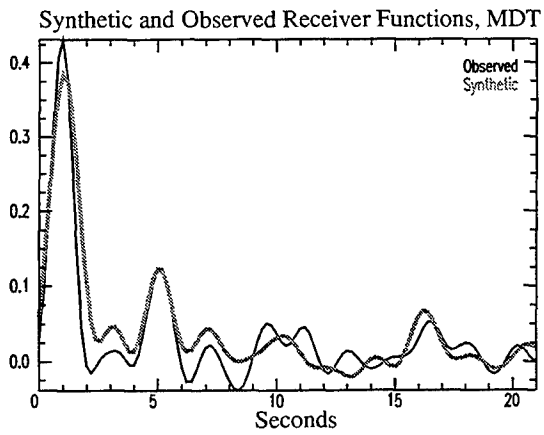
Figure 32

Station KEG:

Figure 33

Least-Squares Velocity Model

Initial Velocity Models

Final Velocity Models

Shear -Wave Velocity (km/sec)

Grid Search Velocity Model

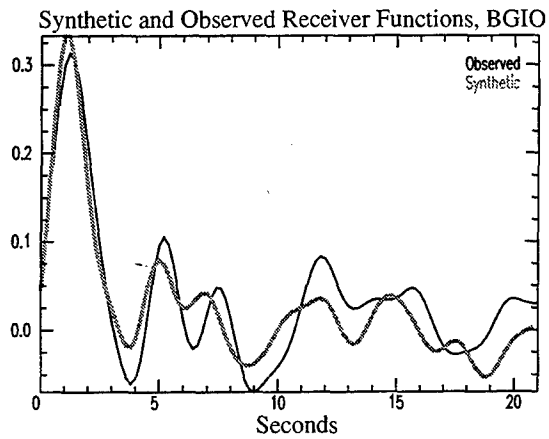A comparison of least-squares inversion (top panels) and grid search inversion (bottom panel) for station BGIO.

Shear -Wave Velocity (km/sec)
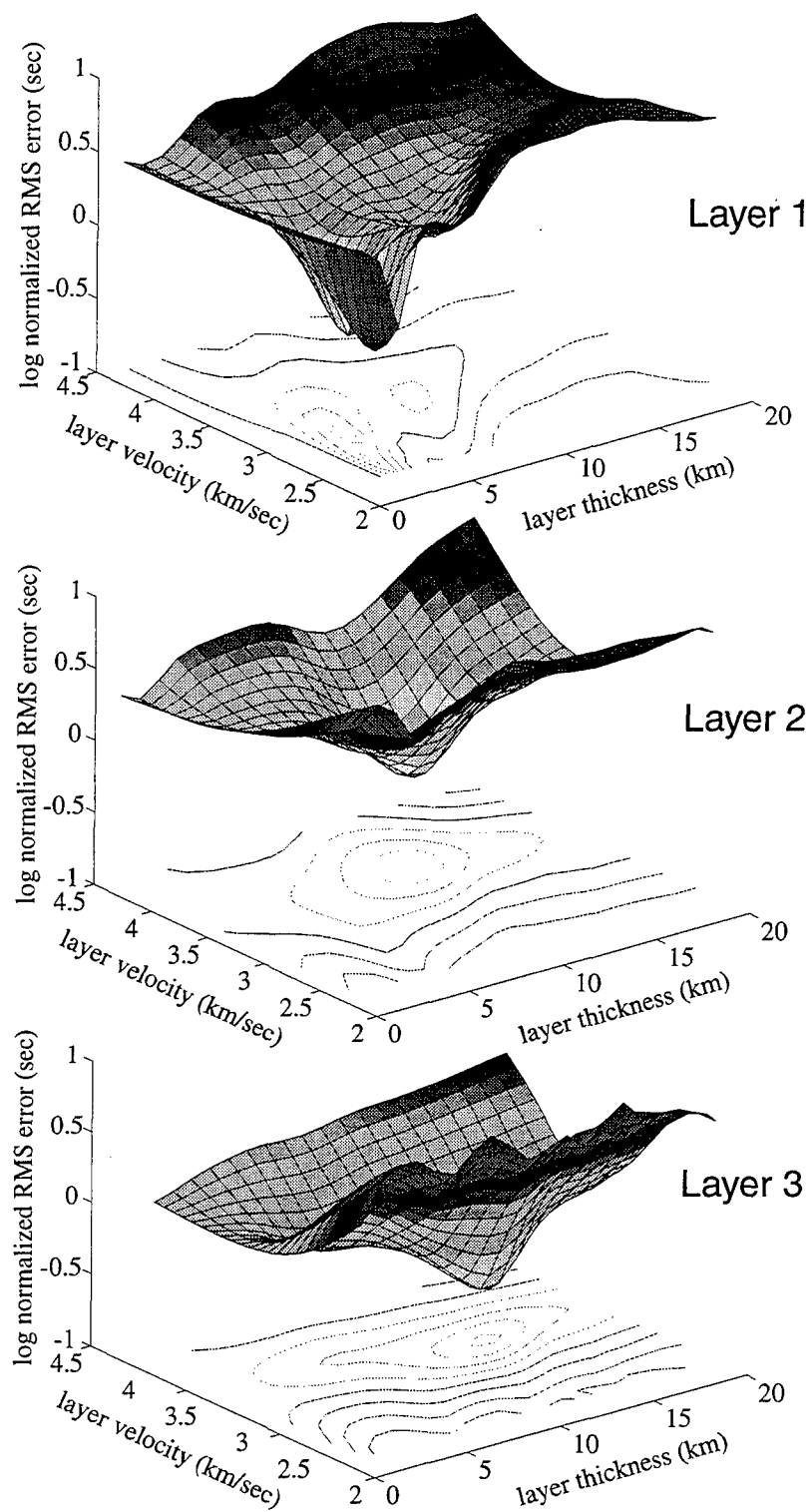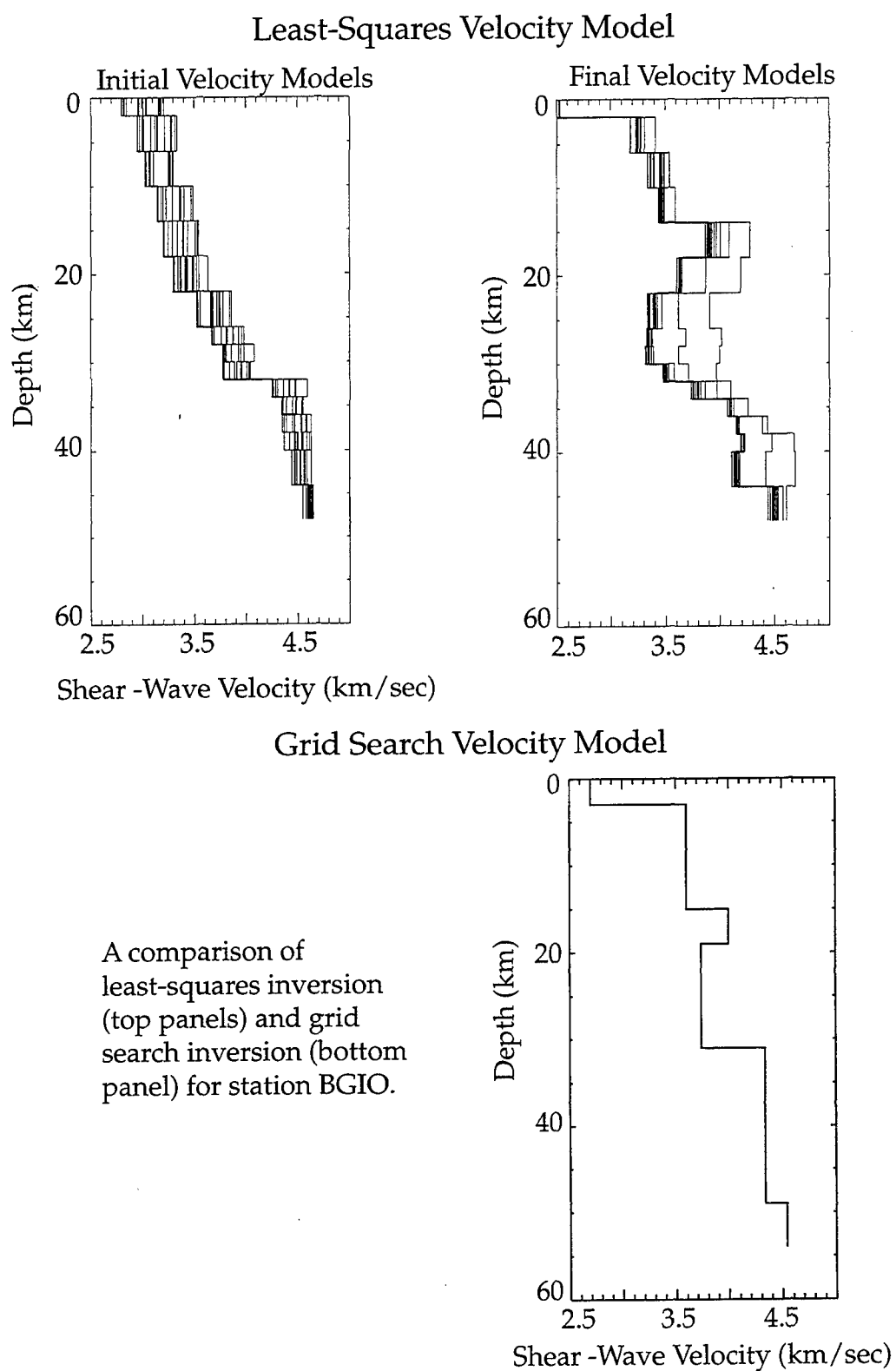
Figure 34

model. There are two relatively large velocity discontinuities: one at 30 km (3.5 km/s to 4.0 km/s) and the other at 40 km (4.0 km/s to 4.5 km/s). Makris et al. (1987) report crustal thicknesses on the order of 30 km (30 to 34 km) which would correspond to the first velocity discontinuity that we observed in our model. For other stations in North Africa we have found that the crust is usually on the order of 40 km thick. However, in the Moroccan Middle Atlas we do find a crustal thickness of 35 km.

We have also found evidence of a pronounced mid-crustal low-velocity zone in central Turkey beneath station ANTO. There has been no prior indication of a low velocity zone in this region although this is a region where the mantle lid is slow and highly attenuating. It is not clear whether this low-velocity zone is related to the heating of the middle crust, some rheological change within the crust or due to 2-dimensional lateral velocity heterogeneity affecting our 1-dimensional model. We have found a Moho depth of 30 km beneath station BGIO which is located near the Dead Sea fault. This crustal thickness is consistent with a refraction profile that was run parallel to the Dead Sea fault (Makris et. al., 1989).

The thickest crust, approximately 55 km, was found beneath station GNI in the Caucasus Mountains. However, data at station GNI are of relatively low quality and contains a fair amount of noise within the stacked receiver function. Also, at station GNI we have observed a large amount of coherent and azimuthally dependent energy which appears on the tangential receiver functions which is an indication of a dipping Moho as well as dipping interfaces within the middle crust.

The above results are currently being used and integrated with other available information to produce an accurate gridded Moho map for the Middle East region.

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APPENDIX I: LIST OF AVAILABLE DATA SETS

Geographic data sets:

- ° Coast lines
- ° Country borders
- ° Rivers
- ° Lakes
- ° Main roads
- ° Main city locations

Geophysical data sets:

- ° PDE seismicity catalogue
- ° ISC seismic catalogue
- ° CMT event locations and focal mechanisms
- ° Short period seismic stations locations
- ° Broad band seismic station locations
- ° Crustal scale seismic and gravity profiles and their interpretations
- ° Bouguer and Free air gravity maps
- ° Moho depth map of Middle East and North Africa
- ° Basement depth map of Middle East and North Africa

Geological data sets:

- ° Complete tectonic map of the Middle East
- ° Mine locations in the Middle East and North Africa

Images:

- ° A complete coverage of the Dead sea fault system in the Middle East

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